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Final Technical Report
April 1980

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MODULAR C^3 INTERFACE ANALYSIS (FLEXIBLE INTRACONNECT) - APPENDIX D INFORMATION THROUGHPUT ANALYSIS ADDENDUM

Martin Marietta Corporation

William G. Bedsole
William F. Kamsler, et al

ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
Griffiss Air Force Base, New York 13441

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This report consists of three volumes. Because of the size of Volume I, it has been divided into two parts. Part 1 contains the basic report and Appendices A through C. Part 2 contains Appendix D.

Volume II, which is classified can be obtained from RADC (DCLT) Griffiss AFB NY 13441.

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Time Division Multiple Access	Fiber Optics
Data Communications	Data Bus Communications
Local Communications Networks	Tactical Command and Control
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report documents the preliminary design for a high capacity wide-band general purpose data/communications busing system. The bus, called a "Flexible Intraconnect," will be used to achieve modularity in the design, implementation and deployment of command, control and communications (C^3) centers of the Tactical Air Force (TAF). FI design requirements were established by estimates of traffic loads for current and future (through 1980) configurations of Tactical Air Control System

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(TACS) C^3 centers of the TAF. Surveys of data distribution system architectures, current and developing technologies, and device interfaces are provided. A design of a Flexible Intraconnect having high transmission rate and capacity, positive flow control and configuration flexibility is described. A standardized interface for physical and functional device to bus access is described. Description of the major functional elements of the FI are provided along with top level block diagnosis. The design was analyzed and preliminary estimates of error performance, reliability, capacity and response times were developed.

Block 18 cont'd

This report consists of three volumes. Because of the size of Volume I, it has been divided into two parts. Part 1 contains the basic report and Appendices A through C. Part 2 contains Appendix D.

Volume II, which is classified can be obtained from RADC (DCLT) Griffiss AFB NY 13441.

Volume III contains the Executive Summary.

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1.0 OBJECTIVES

The objectives of this analysis are to: 1) Determine the information throughput of the flexible intraconnect in terms of blocks per second and megabits per second, and (2) determine the system response time, probability of block delay, and probability of blockage. These determinations are to be made as a function of a given set of ten scenarios, intraconnect design conditions, and other general conditions as stated in Paragraphs 2.0 and 3.0.

2.0 ITEM DESCRIPTION

For the purpose of this analysis, the flexible intraconnect (FI) is configured in ten scenarios. Figures 2-1 through 2-7 depict Scenarios a-g. Scenario h adds a 1 Mb/s virtual bus to g with 2 virtual bus members per LI. Scenario i adds a 5 Mb/s virtual bus to h with 2 more members per LI. Scenario j adds a 10 Mb/s virtual bus to i, again, with 2 new members per LI. Information throughput, delay, and blockage probabilities are determined for each of the scenarios. Each scenario is analyzed for the six different rate conditions shown in Table 2-1.

TABLE 2-1. FI RATES, MB/S.

	1	2	3	4	5	6
LI	50	100	100	100	200	200
EI	100	50	100	200	100	200

3.0 CONSTRAINTS AND ASSUMPTIONS

The following constraints and assumptions apply to this analysis:

1) All telephones are assumed to be off-hook 100% of the time, i.e., a 100% off-hook factor. This establishes the premise that the links between callers will remain fixed throughout the analysis.

2) All telephones are operating at 64 kb/s. The message formulation interval determined from previous reports is 18 ms.

3) All ADP equipment is operating at a rate of 25 ms per block and is used 100% of the time.

4) All blocks are full 1024 18-bit words.

5) The EI end-to-end transmission distance is 1 km minimum and 16 km maximum.

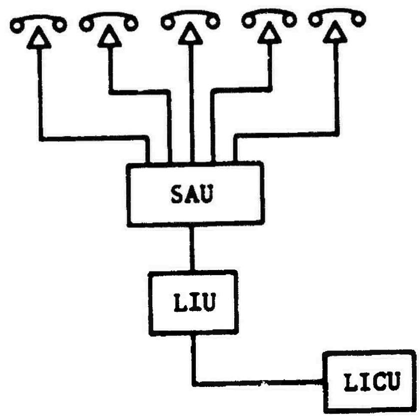

Figure 2-1.
One LI - five telephones -
one LIU (Scenario a).

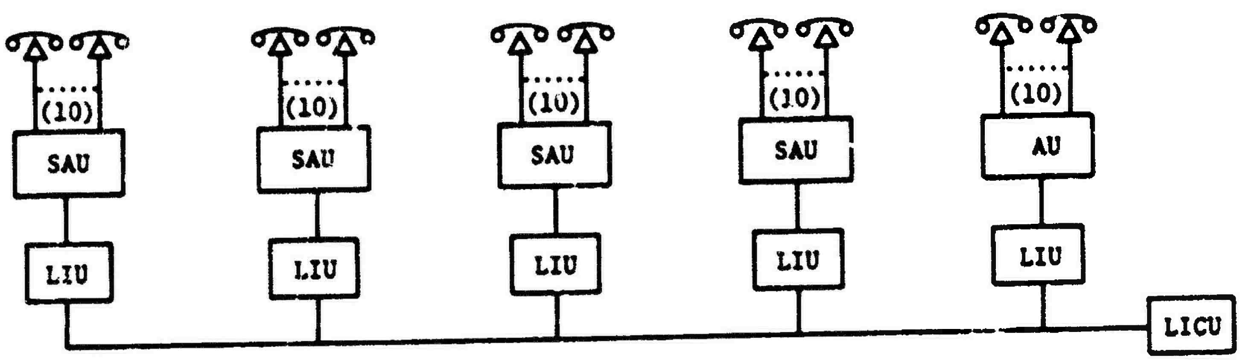

Figure 2-2. One LI - 50 telephones - five LIUs (Scenario b).

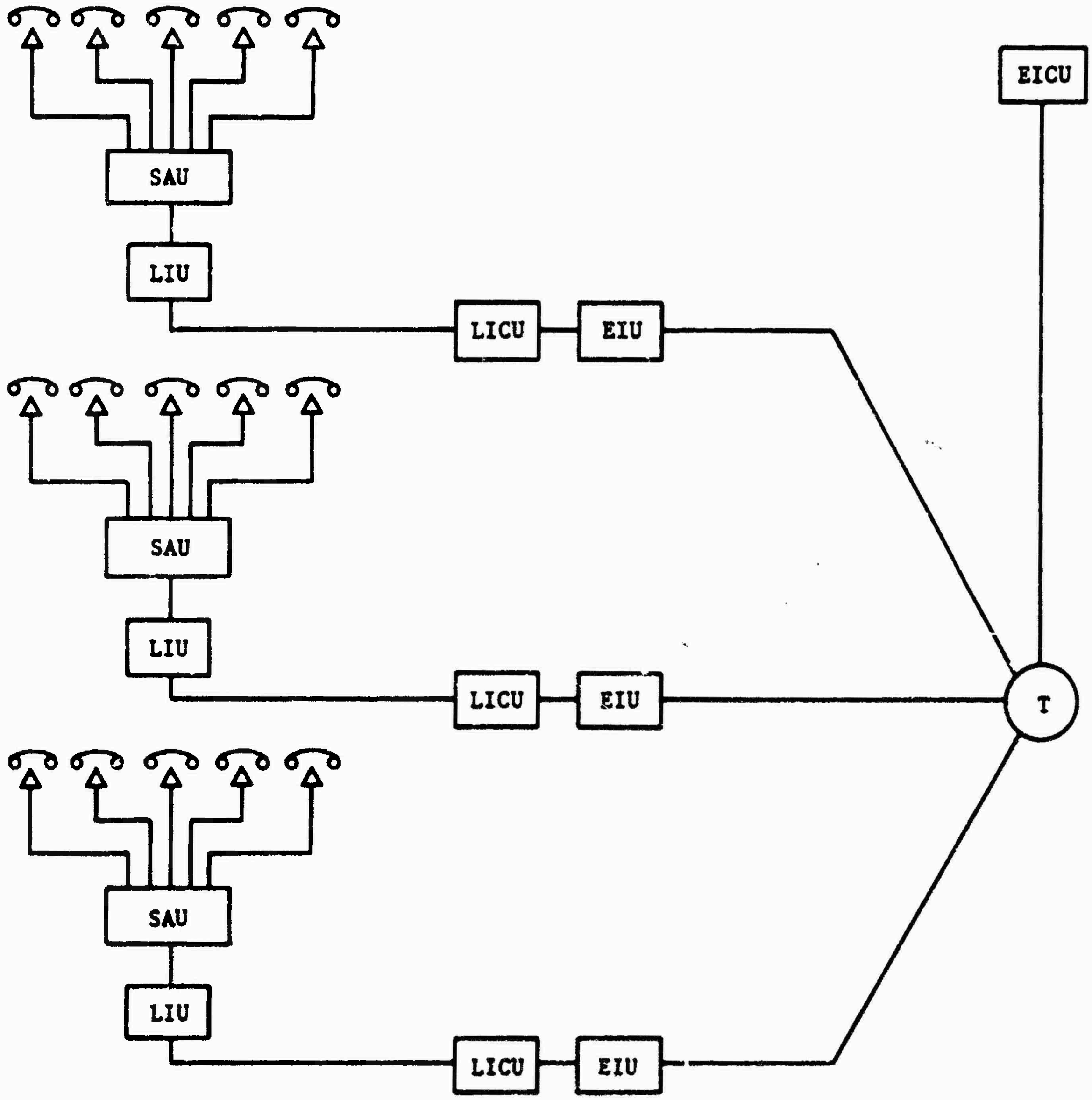

Figure 2-3.
Three LIs - five telephones each - one LIU per LI (Scenario c).

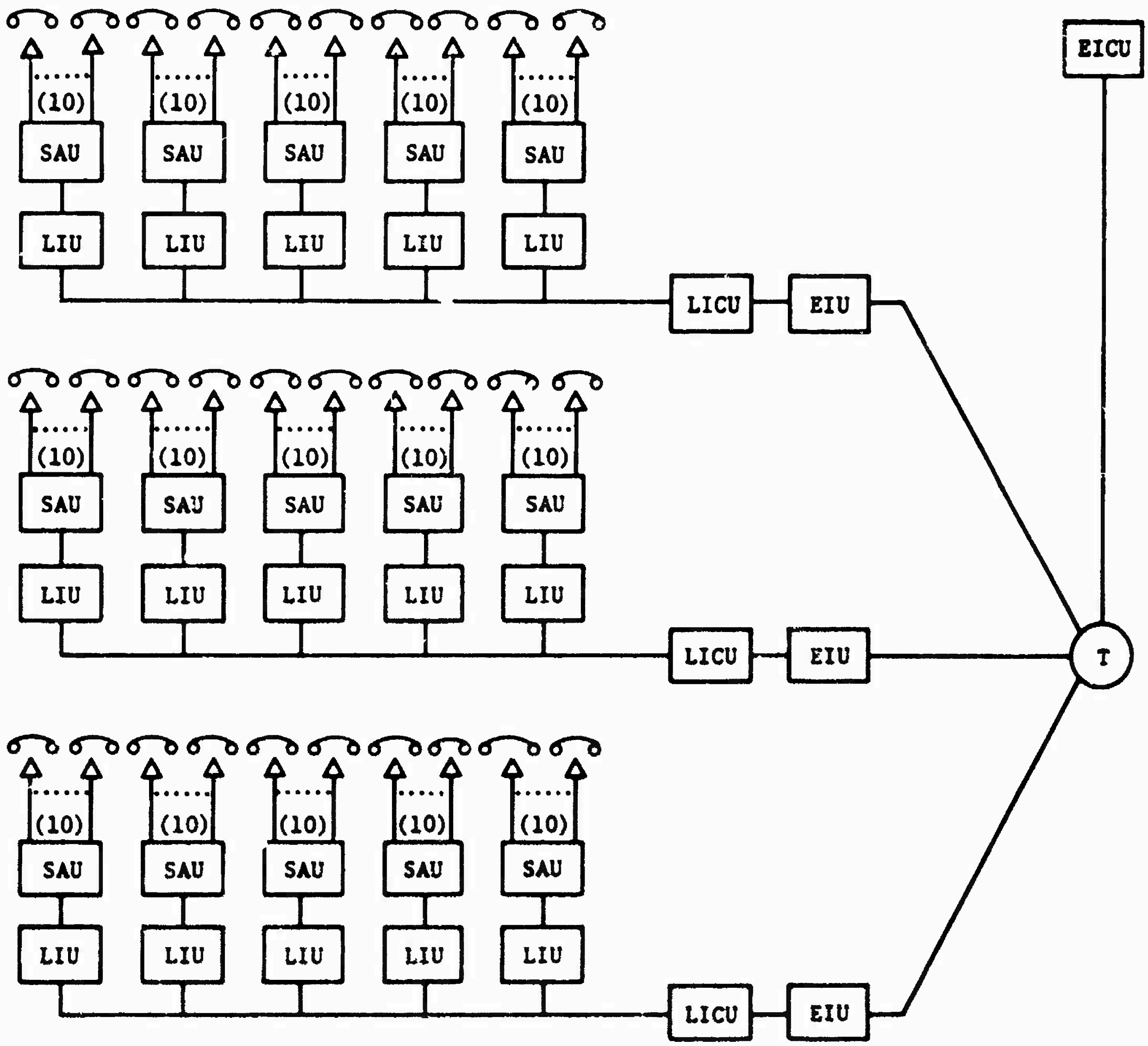

Figure 2-4.
Three LIs - 50 telephones each - five LIUs per LI (Scenario d).

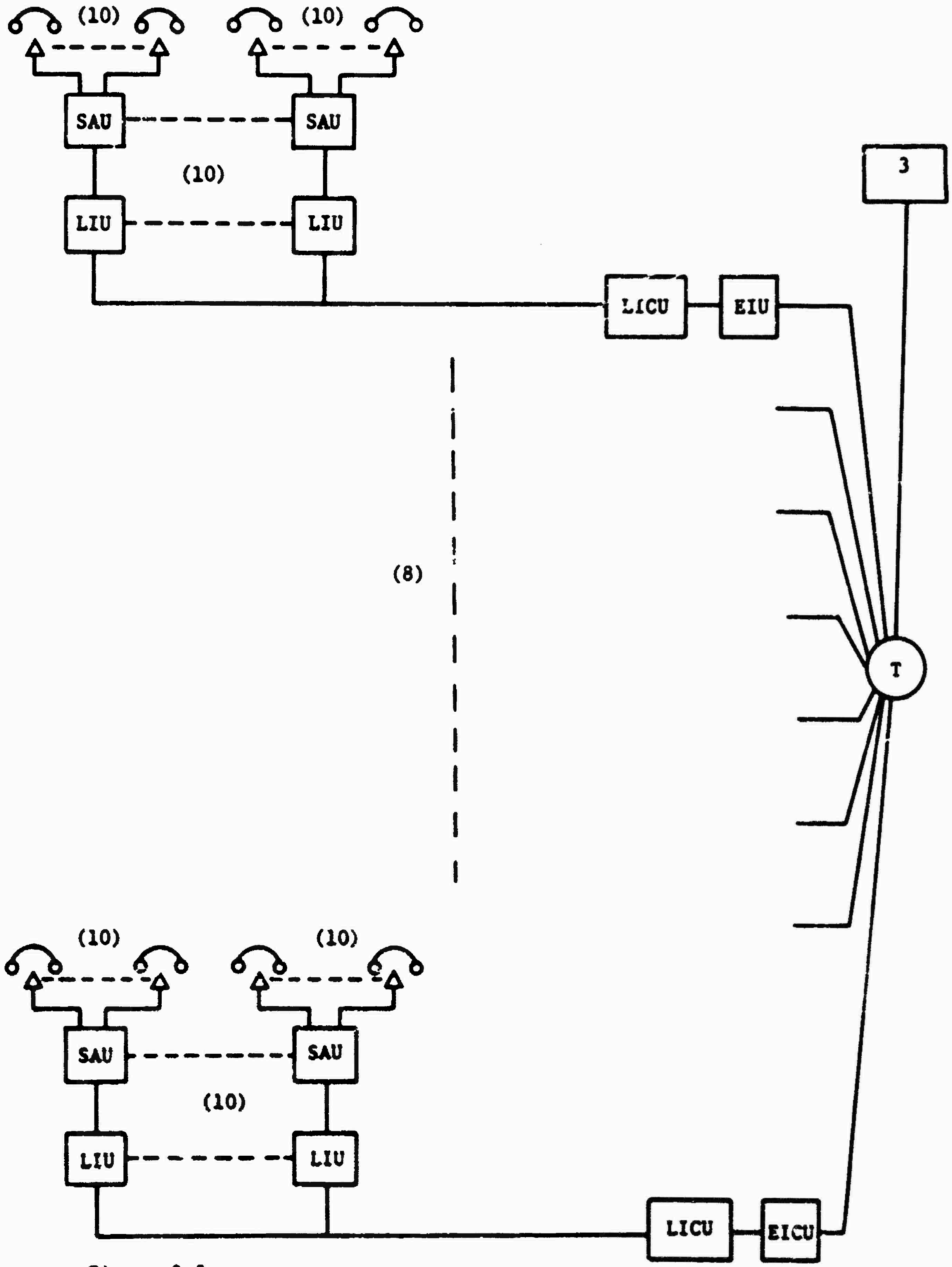

Figure 2-5.
Eight LIs - 100 telephones each - ten LIUs per LI (Scenario e).

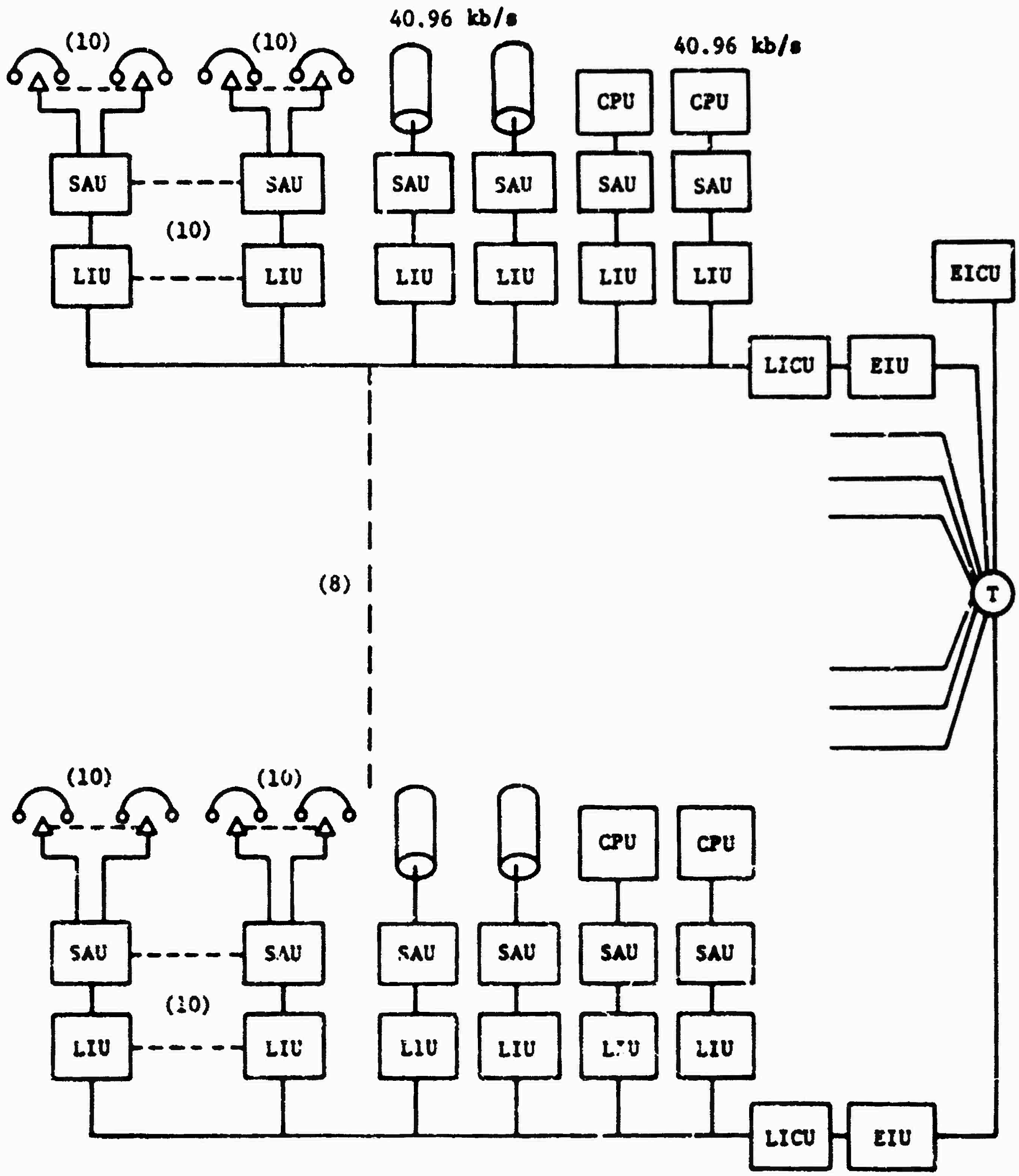

Figure 2-6. Eight LIs - 100 telephones; two disks; two processors each (Scenario f).

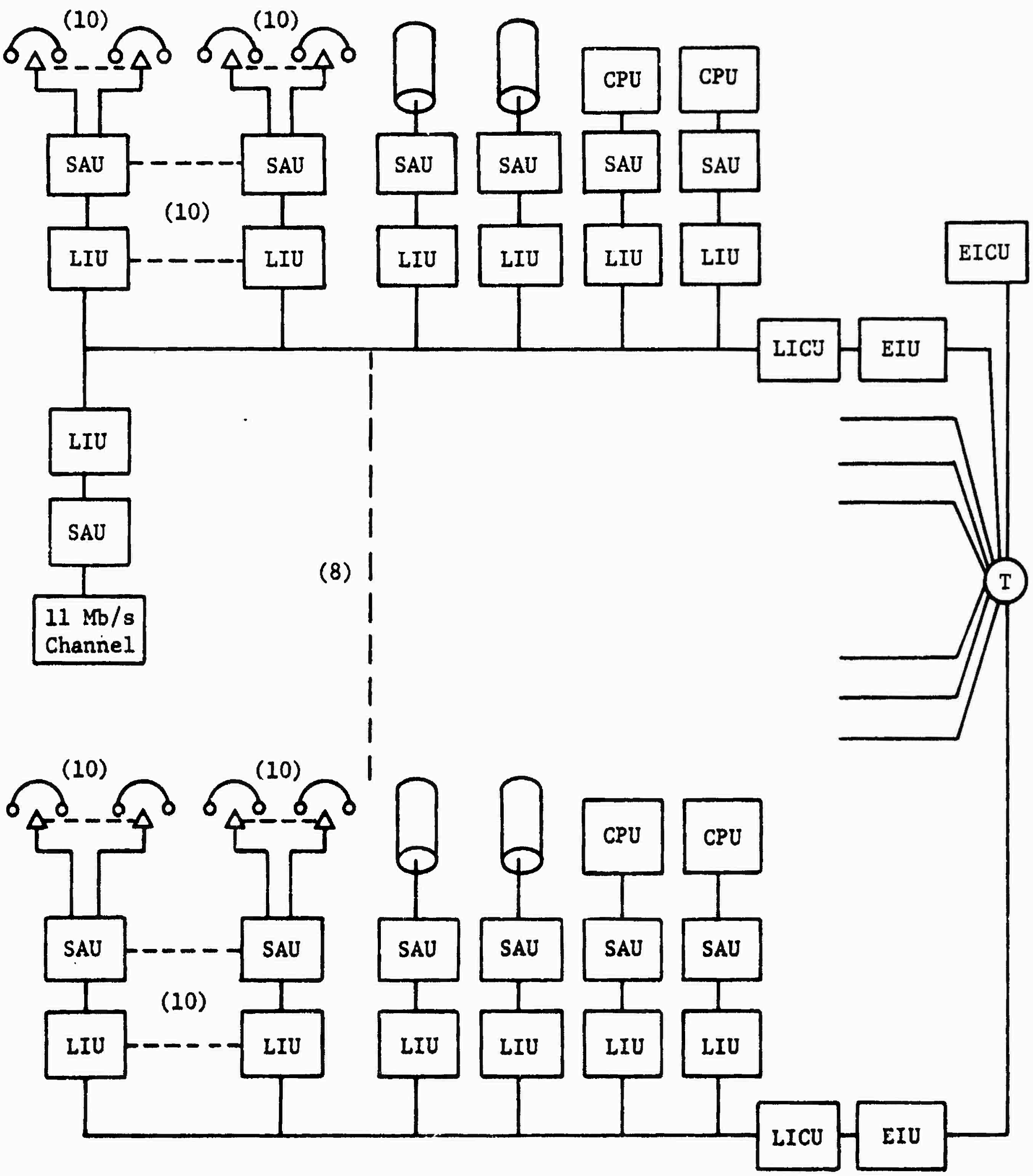

Figure 2-7. Eight LIs - 100 telephones; two disks; two processors each with one 11-Mb/s channel (Scenario g).

6) System functions such as hardware and software processing times, polling algorithms, and transmission protocols are based on the intraconnect design produced in the first phase of the FI study.

4.0 ANALYSIS APPROACH

The analysis has been performed in the following manner:

A system throughput model has been made that defines all the time intervals of interest from end-to-end through the FI system. The model puts the system functions of queuing and polling delays, message transmission times, and FI propogation times, in general terms. The model is then used to determine throughput results for each of the ten scenarios. Throughput is expressed as a function of time, based on the time encountered by a block of data or a message in transiting the FI.

Queuing delays are taken into account at each of the rate interfaces of the FI, i.e., at the device/LI, LI/EI, EI/LI, and LI/device interfaces. Queuing delays are based on a Gaussian distribution of polling irregularities and asynchronism at each of the rate interfaces.

Certain system functions are more conducive to bandwidth considerations than to time. System capacities, loads, and efficiencies are determined for the scenarios and expressed in terms of bandwidth.

Probability of block delay and probability of blockage have been determined from the system throughput analysis.

Conclusions have been drawn in relation to the objective of the study.

During the study, several related topics have emerged that require further study, such as a recommendation for a more comprehensive throughput analysis, a determination of maximum queue size requirements, a new SAU design for COM, and COMSEC considerations.

5.0 RESULTS

5.1 System Throughput.

A model has been established as a basis for determining transmission and throughput characteristics of the FI for all user scenarios required in the analysis. The model defines, in general terms, the delays encountered by messages traversing the FI from device to device. The model for a direct address (point-to-point) message is shown in Figure 5-1 and the model for a virtual

Direct Address (Point-to-Point)

$$\overset{\Delta t_1}{\underline{\text{Device-to-LIU; Poll}}}\left(\begin{matrix}18\text{ ms}\\ \text{or}\\ 25\text{ ms}\end{matrix} + 0.9258\ T_{PLI}\right) + \overset{\Delta t_2}{\underline{\text{Q/R Processing \& Xmission}}}\left(36/BR_{LI} + 55\ \mu s + 144/BR_{LI}\right) + \overset{\Delta t_3}{\underline{\text{Data Xmission (LIU-LICU-EIU)}}}\left(37{,}872/BR_{LI}\right)$$

$$+ \overset{\Delta t_4}{\underline{\text{Queue (LI/EI)}}}\left(\begin{matrix}9\text{ ms}\\ \text{or}\\ 12.5\text{ ms}\end{matrix} + 0.9258\ T_{PEI}\right) + \frac{\overset{\Delta t_5}{\text{Poll/Q/R Processing and Xmission}}}{(95\ \mu s + 216/BR_{EI} + 3t_p} + \frac{\overset{\Delta t_6}{\text{Data Xmission (EIU-EIU)}}}{(18{,}972/BR_{EI} + t_p)}$$

$$+ \frac{\overset{\Delta t_7}{\text{Queue (EI/LI)}}}{(1.9258\ T_{SI})} + \frac{\overset{\Delta t_8}{\text{Poll; Q/R (LICU-LIU)}}}{(36/BR_{LI} + 55\ \mu s + 144/BR_{LI})} + \frac{\overset{\Delta t_9}{\text{Data Xmission (EIU-LICU-LIU)}}}{(37{,}872/BR_{LI})} + \frac{\overset{\Delta t_{10}}{\text{Queue; LIU-Device}}}{(1.9258\ T_{SI})}$$

Note:

1) Total FI Xmission Time $= \sum_{\Delta t_1}^{\Delta t_{10}} \Delta t$

2) Δt_1 - 18 ms for Com; 25 ms for ADP

3) Δt_4 - 9 ms for Com; 12.5 ms for ADP

TERMS

T_{PLI}: The interval between successive polls on the LI. (Not the the interval between polls to a particular LIU).

BR_{LI}: Bit rate on the LI.

T_{PEI}: The interval between successive polls on the EI.

BR_{EI}: Bit rate on the EI.

t_p: Propogation time on the EI.

T_{SI}: The time to transfer one 18,720 bit message across the standard interface (can be at the device receiving rate up to 5-Mw/s, or, later 10-Mw/s).

Figure 5-1. Message transmission and throughput delay model.

bus is shown in Figure 5-2. For convenience, ten time intervals have been identified, Δt_1 through Δt_{10}. The total transmission time encountered by a message is the sum of the time intervals. Since Com and ADP devices are sampled at different intervals, the throughput delays are different. The option is given for selecting intervals of 18 ms for Com and 25 ms for ADP. The effects of delays due to: 1) Waiting for polls; 2) poll, query/response, and message processing, formulation, and transmission; 3) propagation delays; and 4) queuing are shown as functions of LI and EI transmission rates.

Virtual Bus

$$\overset{\Delta t_1}{\frac{\text{Device-to-LIU, Poll}}{(1/\text{VB Rate} + 0.9258\ T_{PLI})}} + \overset{\Delta t_2}{(0)} + \overset{\Delta t_3}{\frac{\text{Data Xmission (LIU-LICU-EIU)}}{(37{,}872/BR_{LI})}}$$

$$+ \overset{\Delta t_4}{\frac{\text{Queue (LI/EI)}}{(1/2\ \text{VB Rate} + 0.9258\ T_{PEI})}} + \overset{\Delta t_5}{\frac{\text{Poll Xmission}}{(180/BR_{EI} + t_P)}} + \overset{\Delta t_6}{\frac{\text{Data Xmission (EIU-EIU)}}{(18{,}972/BR_{EI} + t_P)}}$$

$$+ \overset{\Delta t_7}{\frac{\text{Queue (EI/LI)}}{(0.9258\ T_{PLI})}} + \overset{\Delta t_8}{(0)} + \overset{\Delta t_9}{\frac{\text{Data Xmission (EIU-LICU-LIU)}}{(37{,}872/BR_{LI})}} + \overset{\Delta t_{10}}{\frac{\text{Queue; LIU-Device}}{(1.9258\ T_{SI})}}$$

Figure 5-2. Message transmission and throughput delay model.

The time intervals have been derived by separately considering: 1) Throughput on the LI, 2) throughput on the EI, and 3) the total throughput on the FI for both direct address and virtual bus messages. Model derivation is explained with subsequent calculations of the throughput for the various scenarios on the FI. Calculations of packet rates and bit rates for each scenario are also included in this section. Calculation details follow this section with summaries of the results in Tables 5-1 and -2.

TABLE 5-1. THROUGHPUT DELAYS (ms)(Cont).

			LI Only			1 km EI						16 km EI					
LI (Mb/s)			50	100	200	50	100	100	100	200	200	50	100	100	100	200	200
FI (Mb/s)			--	---	---	100	50	100	200	100	200	100	50	100	200	100	200
Scenario																	
a		Com	69.71	69.52	69.42												
b		Com	56.38	56.19	56.09												
c		Com	69.71	69.52	69.42	102.49	101.92	101.73	101.63	101.54	101.25	102.79	102.22	102.03	101.94	101.65	101.56
d		Com	56.38	56.19	56.09	71.38	70.81	70.62	70.52	70.24	70.14	71.69	71.12	70.93	70.83	70.54	70.45
e		Com	54.71	54.52	54.43	67.14	66.58	66.38	66.29	66.00	65.91	67.45	66.88	66.69	66.59	66.31	66.21
f		Com	54.44	54.25	54.16	66.35	65.78	65.59	65.49	65.21	65.11	66.66	66.09	65.90	65.80	65.52	65.42
		ADP	74.38	74.69	74.59	90.33	89.77	89.57	89.48	89.19	89.10	90.64	90.07	89.88	89.78	89.50	89.40
g	11 mb/s Ch. LI	Com	53.21	53.02	52.93	65.16	64.59	64.40	64.30	64.01	63.92	65.46	64.89	64.70	64.61	64.32	64.22
		ADP	73.69	73.50	73.40	89.14	88.57	88.38	88.28	88.00	87.90	89.44	88.87	88.68	88.59	88.30	88.20
		11 mb/s Ch.	1.16	0.97	0.88	4.21	3.64	3.45	3.35	3.07	2.97	4.52	3.95	3.76	3.66	3.37	3.28
	Other LIs	Com	54.44	54.25	54.16	66.28	65.71	65.52	65.42	65.14	65.04	66.59	66.02	65.83	65.73	65.45	65.35
		ADP	74.88	74.69	74.59	90.26	89.69	89.50	89.40	89.12	89.02	90.57	90.00	89.81	89.71	89.43	89.33
h	11 mb/s Ch. LI	Com	53.13	52.94	52.85	63.95	63.38	63.19	63.09	62.81	62.71	64.26	63.69	63.50	63.40	63.12	63.02
		ADP	73.61	73.42	73.32	87.93	87.36	87.17	87.07	86.79	86.69	88.24	87.67	87.48	87.38	87.10	87.00
		11 mb/s Ch.	1.08	0.89	0.80	3.01	2.44	2.25	2.15	1.87	1.77	3.32	2.75	2.56	2.46	2.17	2.08
		1 mb/s VB	0.88	0.69	0.59	2.07	1.50	1.31	1.21	0.93	0.83	2.22	1.65	1.46	1.37	1.08	0.99
	Other LIs	Com	53.21	53.02	52.93	64.03	63.46	63.27	63.17	62.89	62.79	64.34	63.77	63.58	63.48	63.20	63.10
		ADP	73.69	73.50	73.40	88.01	87.44	87.25	87.15	86.87	86.77	88.32	87.75	87.56	87.46	87.18	87.08
		1 Mb/s VB	0.95	0.76	0.67	2.55	1.98	1.79	1.69	1.41	1.31	2.70	2.13	1.94	1.85	1.56	1.47

TABLE 5-1. THROUGHPUT DELAYS (ms) (Concl).

			LI Only			1 km EI						16 km EI					
LI (mb/s)			50	100	200	50	100	100	100	200	200	50	100	100	100	200	200
FI (mb/s)			--	---	---	100	50	100	200	100	200	100	50	100	200	100	200
Scenario																	
4	11 mb/s Ch. LI	Com	53.10	52.92	52.82	63.84	63.27	63.08	62.98	62.70	62.60	64.15	63.58	63.39	63.29	63.01	62.91
		ADP	73.59	73.40	73.30	87.82	87.25	87.06	86.96	86.68	86.58	88.13	87.56	87.34	87.28	86.99	86.89
		11 mb/s Ch.	1.05	0.87	0.77	2.90	2.33	2.14	2.04	1.76	1.66	3.21	2.64	2.45	2.35	2.06	1.97
		1 mb/s VB	0.85	0.66	0.56	2.71	2.14	1.95	1.85	1.57	1.47	2.86	2.29	2.10	2.01	1.72	1.63
		5 mb/s VB	0.85	0.66	0.56	2.71	2.14	1.95	1.85	1.57	1.47	2.86	2.29	2.10	2.01	1.72	1.63
	Other LIs	Com	53.13	52.94	52.85	63.87	63.30	63.11	63.01	62.73	62.63	64.18	63.61	63.42	63.32	63.04	62.74
		ADP	73.61	73.42	73.32	87.85	87.28	87.09	86.99	86.71	86.61	88.16	87.59	87.37	87.31	87.02	86.92
		1 mb/s VB	0.88	0.69	0.59	2.74	2.17	1.98	1.88	1.60	1.50	2.89	2.32	2.13	2.04	1.75	1.66
		5 mb/s VB	0.88	0.69	0.59	2.74	2.17	1.98	1.88	1.60	1.50	2.89	2.32	2.13	2.04	1.75	1.66
5	11 mb/s Ch. LI	Com	53.09	52.91	52.81	63.79	63.22	63.03	62.93	62.65	62.55	64.10	63.53	63.34	63.24	62.96	62.86
		ADP	73.57	73.38	73.28	87.77	87.20	87.01	86.91	86.63	86.53	88.08	87.51	87.29	87.23	86.94	86.84
		11 mb/s VB	1.04	0.86	0.76	2.85	2.28	2.09	1.99	1.71	1.61	3.16	2.59	2.40	2.30	2.01	1.92
		1 mb/s VB	0.83	0.63	0.53	2.66	2.09	1.90	1.80	1.52	1.42	2.81	2.24	2.05	1.96	1.67	1.58
		5 mb/s VB	0.83	0.63	0.53	2.66	2.09	1.90	1.80	1.52	1.42	2.81	2.24	2.05	1.96	1.67	1.58
		10 mb/s VB	0.83	0.63	0.53	2.66	2.09	1.90	1.80	1.52	1.42	2.81	2.24	2.05	1.96	1.67	1.58
	Other LIs	Com	53.10	52.92	52.82	63.80	63.21	63.04	62.94	62.65	62.56	64.11	63.54	63.35	63.25	62.97	62.87
		ADP	73.59	73.40	73.30	87.74	87.21	87.02	86.92	86.64	86.54	88.09	87.52	87.30	87.24	86.95	86.85
		1 mb/s VB	0.85	0.66	0.55	2.67	2.10	1.91	1.81	1.53	1.43	2.84	2.25	2.06	1.97	1.68	1.59
		5 mb/s VB	0.85	0.66	0.56	2.67	2.10	1.91	1.81	1.53	1.43	2.84	2.25	2.06	1.97	1.68	1.59
		10 mb/s VB	0.85	0.66	0.56	2.67	2.10	1.91	1.81	1.53	1.43	2.84	2.25	2.06	1.97	1.68	1.59

TABLE 5-2 BUS RATES

Scenario		LI			FI	
					Bits/s	
		Packets/S	Bits/S	Packets/S	1 km EI	16 km EI
a	VB	55.56	1.06 M			
b	VB	277.78	5.3 M			
c	VB	55.56	3.21 M		3.25 m	3.31 m
	DA	111.11		166.67		
d	VB	277.78	16.17 M		16.68 m	18.28 m
	DA	555.56		833.34		
e	VB	555.56	32.67 M		91.98 m	112.39 m
	DA	1111.11		4444.44		
f	VB	555.56	38.89 M		117.23 m	138.97 m
	DA	1431.11		5724.44		
g	VB	555.56	62.66 M		216.54 m	262.51 m
	DA	2027.90		6321.23		
h	VB	609.81	63.70 M	54.25	217.58 m	263.56 m
	DA	2027.90		6321.23		
i	VB	881.08	68.87 M	325.52	222.79 m	269.00 m
	DA	2027.90		6321.23		
j	VB	1423.61	79.22 M	868.05	233.24 m	280.40 m
	DA	2027.90		6321.23		

5.1.1 Direct Address Messages.

5.1.1.1 LIU-LIU/LICU Transfer. The first step in sending a message across the FI is to transmit from the DTE to LIU. A Com LIU is polled by the LICU every 18 ms. Since the Com devices in each scenario described are considered 100% off-hook, there will be a packet for transmission from the Com LIU every 18 ms. The maximum transfer time between a Com DTE and the LIU is 1/64 kb/s = 15.6 ms. The processing time in the LIU to modify a device header, formulate and attach a network header to the data, and form a query message is estimated to be 150 μs. These events are accomplished during the 18 ms, thus they are not reflected in the throughput model. In the ADP case, a packet is ready for transmission every 25 ms. These time periods indicate the average time for a packet to be transmitted from a DTE-to-LIU and output onto the FI. While one packet is being transferred from the DTE-to-LIU, the previous packet could be having its header formulated for transfer onto the FI. There will be a packet on the FI from an individual LIU every 18 ms, in the case of Com.

The interval between successive polls on the LI (T_{PLI}) weighted by the factor 0.9258 represents the queuing delay on the LI and is derived in Section 5.2.

Figure 5-3 represents the various time delays involved in the transmission of a packet on the LI. The time to transmit a packet can be expressed as the number of bits in the packet (including header and trailer) divided by the bit rate on the LI (BR_{LI}). Since a poll, query, and query response message each contain 4 words in the message, the time to transmit each would be (36 bits/w x 4w)/BR_{LI} = 144/BR_{LI}. The first word of a query identifies it as such along with the source address, thus giving the destination LIU enough information to begin forming the query response. The estimated time to form a query response (55 ms) is greater than the time to transmit a query (t(max) = 144/50 x 10^6 = 2.88 μs) and, thus, should be reflected in the total LI packet delay. The time to form the other types of messages and headers is not included because they are formed in parallel with other processes. While data is being transmitted, the LICU can form its next poll. The size of a data packet is defined as being 512 data words + 8 device header words + 6 network header and trailer words = 526 words. This gives a transfer time of (36 bits/w x 526 w)/BR_{LI} = 18936/BR_{LI}. The fastest time for this transfer is 18,936/200 x 10^6 = 94.68 μs, which gives plenty of time to form the next poll. The times for forming the query and data headers and trailers are included in the initial waiting times in the LIU (18 ms for Com and 25 ms for ADP).

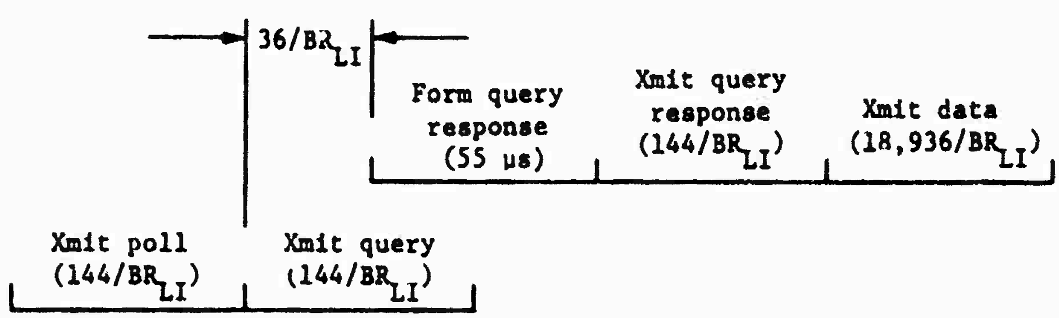

Figure 5-3. Direct address LIU-LIU/LICU delays.

The average propagation delay over a ribbon cable (at 1.5 ns/ft) in a shelter can be estimated to be 30 ns which is negligible and can be omitted from the calculations without any noticeable effect.

Figure 5-3 shows the required time to transfer a packet on the LI from LIU-to-LIU/LICU. This turns out to be a total of $144/BR_{LI}$ + $36/BR_{LI}$ +55 + $144/BR_{LI}$ + $18,936/BR_{LI}$ = 55 + $19,260/BR_{LI}$.

In estimating the throughput of a data packet, the polling transmission time can be ignored since this occurs during the time the packet waits in the source LIU. Δt_2 in Figure 5-1 consists of the time required for a query and corresponding response.

The time to transfer the data ($18,936/BR_{LI}$) is added to the time it takes to transfer the packet across the LICU-EIU interface ($18,936/BR_{LI}$) to form Δt_3

5.1.1.2 EIU-EIU Transfer. Once a packet is received by the EIU, it must await the poll from the EICU. The average time for an EIU to wait for a poll is 18 ms/2 if it contains Com messages and 25 ms/2 if it contains ADP messages. The queuing delay of 0.9258 T_{PEI} is derived in Section 5.2.

Figure 5-4 represents the various time delays involved in the transmission of a packet on the EI. As in the case of the LI, the time to transmit a packet can be expressed as the number of bits in a packet (including start-of-message word, header, and trailer) divided by the bit rate on the EI (BR_{EI}). The time to transmit a poll, query, or query response would be (36 bits/w x 5 w)/BR_{EI} = $180/BR_{EI}$. The poll adds another 30 us to the transfer time because after a packet has been transmitted on the EI, the EICU must determine if the transmitting EIU has more packets to send and modify its poll message accordingly. The time to form a query response is greater than on an LI because it must add the start-of-transmission (SOT) to the network header.

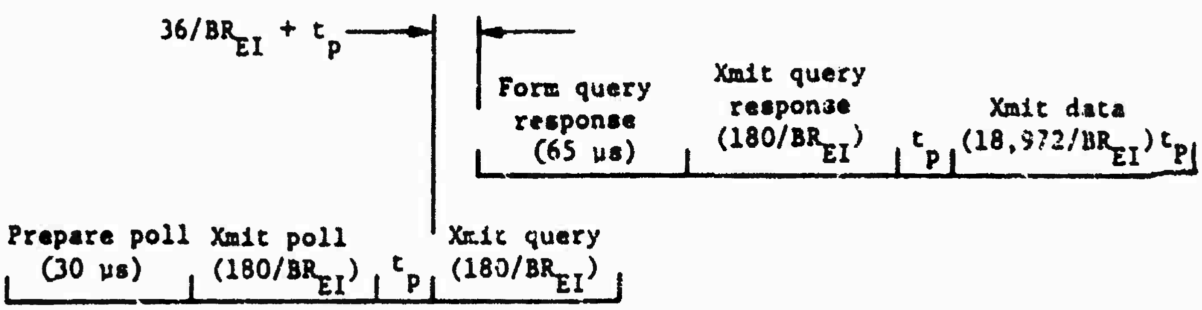

Figure 5-4. Direct address EI delays.

The propagation delay associated with the fiber optic cable used for the EI is 5.1 μs per km. This adds a substantial time element to the information throughput (81.6 μs for 16 km EI) and is included in Figure 5-4.

As with the LI, other processing functions are not included because they are performed in parallel with the processes that are shown. The processes shown represent the largest time intervals required.

Figure 5-4 represents the required time to transfer a packet on the EI from EIU-to-EIU. This transfer time turns out to be $30 + 180/BR_{EI} + t_p + 36/BR_{EI} + t_p + 65 + 180/BR_{EI} + t_p \div 18{,}972/BR_{EI} + t_p = 95 + 19{,}368/BR_{EI} + 4\ t_p$. The packet for the various bit rates on the EI have been calculated with the results shown in Table 5-1.

As with the LI, when estimating the throughput of a data packet, the polling preparation and transmission times can be ignored since this occurs during the time the packet waits in the source EIU. Δt_5 in Figure 5-1 is composed of the time required for a query and corresponding response.

The time to transfer the data is $18{,}972/BR_{EI} + t_p$ as shown for Δt_6.

5.1.1.3 LICU - LIU Transfer. When an EIU receives a data packet off the EI, a queuing delay occurs before the packet can be transmitted onto the LI. This queuing delay of $0.9258\ T_{PLI}$ is derived in Section 5.2.

Figure 5-5 shows the time delays involved in the transfer of a data packet from an LICU-to-LIU. Since the LICU is transmitting the packet, there is no need for a poll. Except for the exclusion of the poll transmission time, the LICU-LIU transfer delays

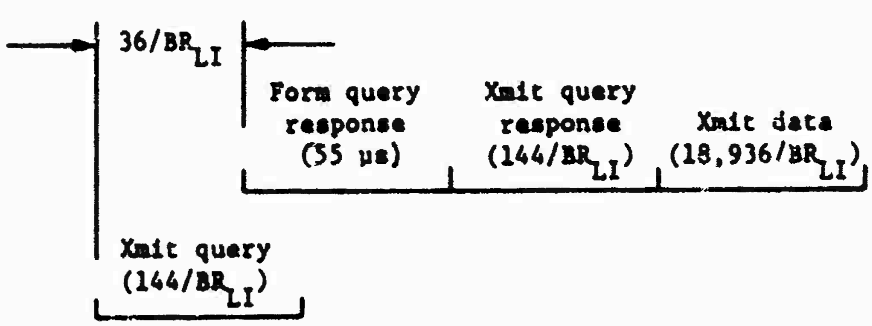

Figure 5-5. LICU-LIU time delays.

are similar to that for an LIU-LIU/LICU (see Fig. 5-1). That is the total transfer time becomes $36/BR_{LI} + 55 + 144/BR_{LI} + 18{,}936/BR_{LI} = 55 + 19{,}116/BR_{LI}$. This value is used to determine the packet rate for the different bit rates on the LI with the results shown in Table 5-1.

Δt_8 in Figure 5-1 consists of the time required for the transmission of a query and corresponding response while Δt_9 reflects the time required to transfer a full data packet across the EIU-LICU interface ($18{,}936/BR_{LI}$) plus the time to transmit the packet to the destination LIU ($18{,}936/BR_{LI}$). Once the data packet is in the LIU buffer, it can wait in queue for a time of 0.9258 T_{SI} as derived in Section 5.2, then transferred to the DTE within a time of T_{SI}. For analysis purposes, T_{SI} is 18 ms for Com devices, 25 ms for ADP devices, (18720 b) /(11 Mb/s) = 1.7 ms for the 11 Mb/s channel, and (1040 w)/(5 Mw/s) = 0.21 ms for a virtual bus.

5.1.2 Virtual Bus.

5.1.2.1 LIU/LIU/LICU Transfer. The device-to-LIU transmission for a virtual bus message is similar to that of a direct address message. The processing within the LIU must include keeping track of the repetition rate and sequence number, but this can be accomplished during the time spent waiting for the next poll. The virtual bus is polled at the virtual bus rate.

Figure 5-6 shows the time delays involved in the transmission of a virtual bus packet on the LI. This omits the delays due to a query and response in the direct address message. This is shown as zero for Δt_2 in Figure 5-2. Δt_3 for a virtual bus remains the same as for a direct address. The total time to transfer a virtual bus packet on the LI is $144/BR_{LI} + 18{,}936/BR_{LI} = 19{,}080/BR_{LI}$.

Xmit poll	Xmit data
($144/BR_{LI}$)	($18{,}936/BR_{LI}$)

Figure 5-6.
Virtual bus LIU-LIU/LICU delays.

5.1.2.2 EIU-EIU Transfer. The average time for a EIU to await a poll from the EICU is 1/2 the polling period which runs at the virtual bus rate. Queuing delays remain the same as for direct address messages because of the assumption of a normal distribution.

Figure 5-7 represents the various delays concerned with the transmission over the EI. There is no need to modify the poll destination address (as in the case of a direct address) because the poll is to a virtual bus number, not a device address. The other differences from a direct address message are the elimination of the times required for a query and response.

Xmit poll $(180/BR_{EI})$	t_p	Xmit data $(18,972/BR_{EI})$	t_p

Figure 5-7. Virtual bus EI delays.

The total transfer time for a virtual bus packet on the EI is $(180/BR_{EI}) + t_p + (18,972/BR_{EI}) + t_p = 19152 + 2\ t_p$. Δt_6 in Figure 5-6 remains the same for a virtual bus as for a direct address.

5.1.2.3 LICU-LIU Transfer. The only difference between an LICU-LIU transfer and an LIU-LICU transfer is the elimination of the poll time. Thus, the total time to transfer a virtual bus packet from the LICU to LIU is $18,936/BR_{LI}$ (Δt_8 in Figure 5-6). The other time delays remain the same as for a direct address.

5.1.3 Bus Rates. The bus rates required to accommodate the traffic described in each scenario have been calculated in terms of packets per second and megabits per second.

One Com LIU contributes a packet rate of 1/18 ms to the LI bus bandwidth since a Com LIU has been defined to be polled every 18 ms. Since Com LIUs communicate locally on a virtual bus, the bit rate would equal the packet rate multiplied by the number of bits transferred (Scenarios a and b).

Since these scenarios are described as containing no switch for the telephones, it is assumed that a Com LIU is directly communicating with only one other Com LIU. This implies that when a Com message is transmitted over the EI, it is directly addressed (it should be destined for a switch). As previously determined, a processing time of 55 μs is added for each packet transferred on the LI. This value multiplied by the number of packets transmitted in a given time gives the total time dedicated for processing during this given time. In order to transmit 55.556 packets in a second, the time for processing these packets (55.56 x 55 μs) should be subtracted from one second to give the actual time available for transfer. The propagation delay associated with this transfer should also be subtracted.

Although the propagation delay is negligible on the LI (thus, not included in the calculations) it proves to be a major factor when calculating required bit rates for the EI. The required bit rate is then determined by dividing the number of bits transmitted during a packet transfer by the time available for this transfer. The number of packets transmitted <u>to</u> an LI has been assumed to be equal (on the average) to the number of packets transmitted <u>from</u> the same LI. Thus, the total rate on the LI is twice the calculated transmission rate. The calculations also take into consideration that an individual Com LIU can be transmitting over the EI while another telephone on the same Com LIU can be communicating locally via intercomm.

A distinction is made in the calculations between a directly addressed packet and a virtual bus packet when specifying the packet rates. As previously determined, a virtual bus packet requires less throughput time, thus, it does not use as much bandwidth as if it were directly addressed.

One ADP LIU contributes a packet rate of 1/25 ms to the LI bus bandwidth since the discs and processors in these scenarios have been designated as operating at a rate of 25 ms per packet. These devices communicate directly rather than on a virtual bus as with Com (Scenario f).

The 11 Mb/s channel requires a packet rate of (11 Mb/s) (1 word/18 bits)/(1024 words) = 596.79 p/s for each LI; but since it is transmitted from only one LI, it only requires a packet rate of 596.79 p/s from the EI (rather than eight times this amount) (Scenario g).

A virtual bus requires a packet rate of (VB rate) (1 word/18 bits)/(1,024 words) = VB rate/18432 from each LI and from the EI (Scenarios h-j).

5.2 Queuing Delays.

Messages encounter several possible queue buildups during their transmission over the flexible intraconnect. A possible queue occurs at each of the interfaces where a change of transmission rate is necessary. These are in the LIU at the LIU-to-LI interface, in the LICU (or EIU) at the LICU-to-EI interface, in the EIU (LICU) at the EIU-to-LICU interface, and in the LIU at the LIU-to-device interface.

Queuing delays may be caused by three things: 1) The fact the EI polling, LI polling, and the device-to-LIU interface are not synchronous, 2) the fact that the load offered to the LI from the device may be greater at any one time than the capacity of the LI, and 3) the fact that messages destined to leave the LI are not necessarily polled at regularly spaced intervals with respect to the LICU polling cycle, and similarly, messages leaving the EI for a particular LICU may not be evenly spaced in time. So while the long-term averages of polling rate are constant the instantaneous polling intervals tend to be irregular. Item 1 causes messages to be delayed simply because they must wait a certain portion of a polling period for the poll to arrive. For example, a message arriving in the LICU (EIU) buffer from the LI must wait on the average 1/2 an EI poll period until the EI Poll arrives to transfer it from the LI. And there is a similar wait for the LICU poll to transfer data from the LIU to the LI. This queue is not load dependent. The second type queue is caused by the fact that a poll will not always arrive, say from EICU to LICU, at an isochronous rate, but will sometime be delayed to service high priority conditions. A high priority condition may be caused by a user having encountered a negative reply to a query, indicating buffer full, and is given a higher polling priority for the next time around. The second condition may be caused by an LI or EI having reached either its transmission capacity, or its queue buffer capacity. In either case the poll is delayed from its normal arrival time and the message waiting to be transferred by it will be further delayed. Item 3 has the effect of "bunching up" of outgoing messages from both the LI and EI instead of producing evenly flowing traffic.

All three catagories of queue delay have random occurrences. The first is uniformly distributed between 0 and one poll interval, so the average may be taken as 1/2 poll interval. Item 2 and 3 have been estimated to follow a Gaussian distribution with a mean about the normal, unperturbed poll time.

Certain assumptions can be made about system operation, particularly regarding polling, as a basis for the analysis of queuing delays. They are:

1) Both EI and LI polling will tend to occur at uniform, isochronous rates. The uniformity of the poll devices will depend upon the delays encountered, but the long-term average of polls per unit time will be a constant. This says that if there were no delays in polling due to priority conditions and all stations were off-hook 100% the polling rate on both the EI and LI would always be evenly spaced at a rate equal to the message rate required by the load.

2) This analysis assumes that a queue buffer will always be of sufficient size and the queue problem is one of determining the queue delay, not the maximum queue size, or blockage due to exceeding queue capacity.

3) Where there is a 100% off-hook factor and all devices are always on the bus there is never a condition where polling is delayed for priority purposes, because an overload condition is prevented by denying access to the FI at the device. This is an abnormal condition, so it will be assumed that polling irregularities will exist as in normal system operation. Otherwise, the queuing problem is trivial. In fact, under those conditions, query and response functions are not necessary since once data is allowed on the FI it can never meet with overload conditions and the querried buffers will never be full. This oversimplifies the analysis and leads to inconclusive results so query and response modes will also be included as in normal system operation.

The preceeding conclusions are based on the assumptions that the FI controller will have the capability to automatically sense the magnitude of the offered load in relation to FI capacity and to deny access to users who are attempting to exceed that capacity. The FI can handle instantaneous overloads due to irregularities in its transmission functions but not long-term average overloads. The load regulating function is the negative response to a query. This alone will regulate the load by denying access on a packet-by-packet basis, which means that there would be gaps of uncontrolled length in transmission during overloads. This is intolerable to devices such as telephones where speech continuity is necessary. It is necessary, then, to deny access to users on a systematic basis, so when they are given access their circuit is continually active.

4) The EICU polling rate to a given LICU will be at the same rate as the LI-to-EI message rate for that LI. This fact should be obvious but it is made to show that although EI and LI polls may occur at a much different rate, the rate of EI-bound messages on the LI is equal to the EI-to-LI poll rate for that LI.

5.2.1 Queuing Delays Caused by Irregularly Spaced Polling Intervals. When we assume a possibility of a negative response to a query indicating a full receiving buffer, or, a "bunched" offered load to a receiving buffer either on the LI or EI then the message will go into a queue and be delayed. The nature of the queue build-up can be described provided the nature of the polling distribution is known. An expression can then be obtained for the length of the queuing delay as a function of the average polling rate. That is the purpose of this section.

Distribution of polling occurrences is difficult to define mathematically. An examination of polling delays due to priorities, and also of irregularly spaced offered loads leads to the conclusion that the polling occurrences may generally be Gaussian distributed about a mean which is the normal, unperturbed polling time. As a first approximation to defining the polling delay (and later the maximum queue size) we have assumed a Gaussian distribution of polling occurrences with a standard deviation of one polling interval. This assumption gives reasonable results, and it may not be necessary to define the polling distribution more rigorously.

The probability distribution for polling occurrences on either the EI or LI is shown in Figure 5-8. From that we can calculate the probability of polling delays (queue build-up), p(p), as a function of polling interval. The probability of polling delay greater than:

One polling interval is $1 - p(p_1)/\sigma$
Two polling intervals is $1 - p(p)/\sigma$
Three polling intervals is $1 - p(p_3)/3\sigma$

where:

$P(P_1) = 0.8413$; $1-p(\sigma) = 0.1587$
$P(P_2) = 0.9772$; $1-p(\sigma) = 0.0228$
$P(P_3) = 0.9987$; $1-p(\sigma) = 0.0013$

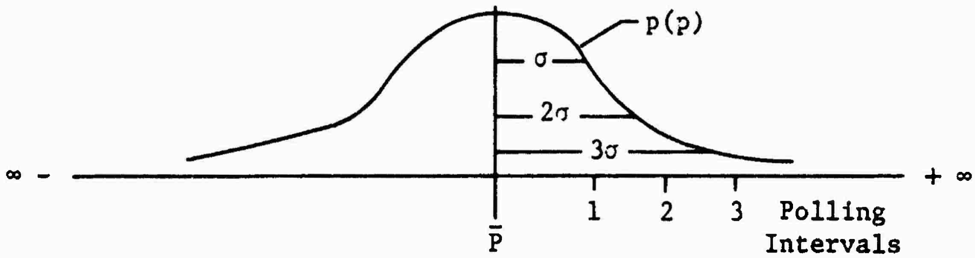

Figure 5-8. Probability of poll occurence p(p).

Since the polls occurring from $-\infty$ to the mean, $\bar{p}$, can be taken as occurring at the normal poll time, $\bar{P}$, only those occuring from $\bar{P}$ to $+\infty$ are delayed. This means that:

1) $0.8413 - 0.5000 = 0.3413$; 34.13% of messages will be delayed by only one poll interval

2) $(0.9772 - 0.5000) - 0.3413 = 0.1359$; 13.59% will be delayed by only 2 poll intervals.

3) $(0.9987 - 0.5000) - 0.4772 = 0.0209$; 2.09% will be delayed by only 3 poll intervals.

4) $0.5000 - 0.4987 = 0.0019$; .19% will be delayed by more than 3 polls.

5) All messages will be delayed by 1/2 poll period, on the average, in addition to 1) through 4) delays.

Therefore, the average queue delay of messages is: (B) x (poll period of the receiving intraconnect) where B is a constant to be determined.

Delay in queue, D_q;

$$D_q = \frac{0.5P}{2} + 0.3413P + 0.1359(2P) + 0.0209(3P) + 0.0019(4P)$$

where P is the poll interval on either the EI or LI.

$$D_q = 0.9258P$$

This means that the expected queue delay is 0.9258 times the poll period of the receiving intraconnect. For instance, in the transition from LI to EI a message can be expected to be delayed by 0.9258 P_{EI} where P_{EI} is the average polling interval taken as a composite of all LICUs not just the one in question. Simularly a message going from EI to an LI will be delayed on the average of 0.9258 P_{LI} where P_{LI} is the composite LI poll rate of all LIUs on the LI.

An assumption made here is that when a message is denied transmission it is assigned a priority and may be transmitted on the very next poll, (not its next normal poll). It may, then, receive several chances to be transmitted by successive polls, and it does not have to wait until its next normal poll time.

The results from $p(P_1, P_2$ and $P_3)$ would indicate that the maximum size of the queue buffer can be determined by considering the message rate on the transmitting intraconnect in conjunction with the polling interval on the receiving intraconnect. These relationships could be useful in a later study when the size of the queue is of interest.

5.2.2 FI Queues.

5.2.2.1 Device-to-LI Queue. When a message is tranferred across the standard interface from device (SAU) to the LI through the LIU it will be delayed in the LIU on the average one half the interval between message formulation periods in the SAU before being tranferred across the SAU-to-LIU interface. It will be delayed another half interval in the LIU waiting for a poll from the LICU. Both delays, then, account for a delay of one interval. For Com data the average delay from quantization to entry of the message in the LIU is 18 ms. ADP data will experience a similar delay of 25 ms. (Note that the composite LI poll period is much shorter than 18 ms or 25 ms and depends upon the number of LI users.) From the LIU the message may be denied access to the LI if the LICU buffer is full (assuming the message is destined for the EI). And if given access it may be put in queue at the LICU (EIU) to wait for the EI poll. The first two delays are on the average 9 ms + 0.9258 P_{LI} for Com and 12.5 ms + 0.9258 P_{LI} for ADP. The LICU queue delay is included in the next paragraph.

5.2.2 LI-to-EI Queue. A message transmitting the LI to EI interface at the LICU may encounter a queue due to a "bunched" offered load from the LI to EI, or from a delayed EI poll to that LICU. Both cases are included in the assumption of a Gaussian polling distribution to deplete the buffer. The queue delay at the LICU (EIU) buffer is 0.9258 P_{EI}. The total LI-to-EI queue includes a half EI poll interval delay, on the average, due to the asynchronous occurrences of LI and EI polling. This delay is 9 ms for Com and 12.5 ms for ADP.

5.2.2.3 EI-to-LI Queue. Messages from the EI to a particular LICU may go into a queue because more than one LICU is sending to it in one EI poll cycle and the transmission may be "bunched" so that their arrival is not uniformly spaced throughout the EI polling cycle. If this bunching is Gaussian distributed, as assumed, the queuing delay is also 0.9258 P_{LI}; where P_{LI} is the polling interval of the receiving LI. This is the LI composite polling interval, not the normal poll interval to that LICU.

5.2.2.4 LI-to-Device Queue. There can be a queue in the LIU due to local LI and EI-to-LI senders destined for one LIU (an ADP device). This traffic can be "bunched" and asynchronous in the same manner as the other transmission. The only difference is the speed at which the LIU-SAU interface, i.e., the standard interface, works. The normal distribution applies to the messages offerings to the LIU, but the depletion is based on the standard interface transfer rate instead of the polling interval. Therefore, the average queuing delay is 0.9258 T_{SI}; where T_{SI} is the interval for the transfer of one message over the standard interface. This is in addition to a message transfer time of one T_{SI} required to transfer the message from LIU to device.

5.3 Bandwidth Considerations.

The loads offered to the FI in each scenario can be expressed in terms of bandwidth as well as in terms of throughput. The bandwidth concept more easily expresses the capacity of the FI to handle traffic loads, but does not take into account queuing delays and, consequently, throughput times. Blocking probabilities may be expressed in terms of bandwidth in these scenarios. The following calculations take into account bandwidth required for: Polling, query, response, message processing, message transmission, and propogation delays for each scenario.

5.3.1 Load Determinations by Scenario.

5.3.1.1 Scenario a. In Scenario a where there is one LI with five telephones attached, the required LI bandwidth is 1.060 Mb/s. Refer to Figure 2-1. The message rate of telephones LIUs is 1/18 ms, or 55.56 messages/s. The number of bits per message, accounting for network and DTE headers, data, and trailer is 18,936 bits. The messages are transmitted over a virtual bus and do not use the EI. The bandwidth required is, therefore, that of the message, BW_M and the LICU Poll, BW_P. Propogation bandwidth over the LI is negligible.

$$BW_{LI} = BW_M + BW_P$$

$$BW_P = N_T(55.56)\ M/S\ (144)\ b/M = 8\ kb/s.$$

where N_T = No. of telephone LIUs

$$BW_M = N_T(55.56)\ M/s\ (18,936)\ b/M = 1.052\ Mb/s.$$

$$BW_u = 1.060\ Mb/s.$$

5.3.1.3 Scenario c. In Scenario c there are three LIs with five telephones each. Each LI requires 5.344 Mb/s, and the EI requir- 6.497 Mb/s. Refer to Figure 2-3. Assumptions:

1) There are both intercom and point-to-point requirements.

2) Intercom is restricted to LI usage and will use virtual busses.

3) There is no switch in the network and each LIU will be required to send and receive two point-to-point messages during one 18 ms period to service the other LIUs.

The bandwidth required on an LI is that required for the intercom, calculated in 5.3.2 added to point-to-point requirements.

The point-to-point bandwidth is based on a message multiplier, N_T, of four, i.e., each LIU transmits and receives a total of four messages during an 18 ms period. Also, message transmit time is taken into account. Message processing time of 55 us has the effect of increasing the message rate from 55.56 M/s to:

$$\frac{1}{18 \times 10^{-3} - 55 \times 10^{-6}}, \text{ or, } 55.72\ M/s.$$

The bandwidth required for point-to-point LI messages is:

$$BW = 4\ (55.72)\ M/s \times 19,260\ b/m = 4.292\ Mb/s.$$

The total LI bandwidth required is:

$$BW_{LI} = 4.292\ Mb/s.\ (P\text{-}P) + 1.052\ Mb/s.\ (IC)$$

$$BW_{LI} = 5.344\ Mb/s.$$

The bandwidth required on the EI is the sum of the point-to-point requirements on the three LIs with the additions of EI network headers to the message and a factor for transmission time on the EI. The message multiple, N_T, is six since each LI sends two messages over the EI in an 18 ms period. Message processing time and propogation time on the EI is 115.4 us/message (for 1 km legs). This has the effect of increasing the message rate to:

$$\frac{1}{18 \times 10^{3} - 115.4 \times 10^{6}}\text{, or, 55.91 M/s.}$$

The bandwidth required for EI messages is then:

$$BW_{EI} = 6\ (55.91)\ \text{M/s} \times 19{,}368\ \text{b/m} = 6{,}497\ \text{Mb/s.}$$

5.3.1.4 Scenario d. In scenario d there are three LIs with 50 telephones each. Refer to Figure 2-4. Each LI requires 26.763 Mb/s and the EI requires 64.971 Mb/s. Assumptions:

1) There are both intercom and point-to-point requirements and the intercom uses local LI virtual busses.

2) We can assume a more practical scenario. One LI is at an operations central, one at a switch, and one at a tech control. This way, a given LIU will only need to transmit to one other LIU in each of the other LIs. Otherwise, an LIU may be required to transmit as many as 10 messages to service all its phones. This would be impractical and unnecessary with a switch and tech control in the center. This means each LIU will produce three messages during an 18 ms interval to service its 10 telephones.

3) The users can be grouped so that all those from one LIU will go to only one other LIU at each of the other two LIs. Each LIU will send only 2 point-to-point messages per 18 ms.

The LI bandwidth required is:

$$BW_{LI(1)} = BW_{LI(2)} = BW_{LI(3)}$$

$$BW_{LI(n)} = BW_{IC} + BW_{PP}$$

$$BW_{IC} = 5 \times 55.56 \times (18{,}936 + 144) = 5.3\ \text{Mb/s.}$$

$$BW_{PP} = 2\ (2\text{x}5) \times 55.72 \times 19{,}260 = 21.463\ \text{Mb/s.}$$

$$BW_{LI(n)} = 26.763\ \text{Mb/s.}$$

The EI bandwidth required is:

BW_{EI} = 60 x 19,368 x 55.91 = 64.971 Mb/s.

5.3.1.5 Scenario e. Scenario e with eight LIs containing 100 telephones each is shown in Figure 2-5. The LI bandwidth required is 32.063 Mb/s. The EI bandwidth required is 86.629 Mb/s. Assumptions:

1) Each LIU will send to only one other LIU outside its LI. This represents the switch or the tech control LI. This means that the multiplying factor, N_T, is 2. It also assumes that the telephones in each LI can be grouped at the SAU by destination and only one message per 18 ms period is required by each LIU. These assumptions will hold throughout the remainder of the scenarios.

The LI bandwidth required is:

$BW_{LI(1)} = BW_{LI(])} = \ldots\ldots\ldots\ldots BW_{LI(n)}$

$BW_{LI(n)} = BW_{IC} + BW_{PP}$

BW_{IC} = 10 x 55.56 x 19,080 = 10.6 Mb/s.

BW_{PP} = 20 x 55.72 x 19,260 = 21.463 Mb/s.

$BW_{(n)}$ = 32.063 Mb/s.

The EI bandwidth required is:

BW_{EI} = 80 x 55.91 x 19,368 = 86.629 Mb/s.

5.3.1.6 Scenario f. Scenario f is the same as e with two discs and two processors added to each LIU. The LI bandwidth required is 38.239 Mb/s. Refer to Figure 2-6. The EI bandwidth required is 111.533 Mb/s. Assumptions:

1) The assumptions are the same as for scenario e.

2) ADP devices are sampled on 25 ms intervals.

3) Each ADP device will communicate with only one other ADP device. The other device may be on any LI. Half the devices will communicate locally and half over the EI.

4) All ADP transmissions are point-to-point.

The bandwidth required for the LI is:

$BW_{(n)} = BW_{TEL} + BW_{ADP}$

$BW_{TEL} = 32.063$ Mb/s. (see e)

$$BW_{ADP} = (4x2) \times \frac{1}{25 \times 10^{-3} - 55 \times 10^{-6}} \times 19260 = 6.176 \text{ Mb/s.}$$

$BW_{(n)} = 38.239$ Mb/s.

The bandwidth required for the EI is:

$BW_{EI(e)} = BW_{TEL} + BW_{ADP}$

$BW_{TEL} = 86.629$ Mb/s. (see e)

$$BW_{ADP} = 32 \times \frac{1}{25 \times 10^{-3} = 115.4 \times 10^{-6}} \times 19368 - 24.906 \text{ Mb/s.}$$

$BW_{EI} = 111.533$ Mb/s.

5.3.1.7 Scenario g. Scenario g is the same as f with the addition of one 11 Mb/s channel to seven other LIs. Refer to Figure 2-7. LI bandwidth required is 50 Mb/s. EI bandwidth required is 123.951 Mb/s. Assumptions: Same as f and;

1) The 11 Mb/s rate refers to the rate of the 1,024 x 18 data bits in the message.

2) The 11 Mb/s channel LIU operate as point-to-point messages, i.e., have poll/query/response operation.

LI bandwidth is:

$BW_{LI(n)} = BW_{TEL} + BW_{ADP} + BW_{CH}$

$BW_{TEL} = 32.063$ Mb/s. (see e)

$BW_{ADP} = 6.176$ Mg/s. (see f)

$$BW_{CH}\text{: Message Rate; } \frac{1}{\frac{(1024 \times 18)}{11 \times 10^{6}} - 55 \times 10^{-6}} = 617 \text{ M/s.}$$

$BW_{CH} = 19{,}080 \times 617 = 11.77$ Mb/s.

$BW_{LI(n)} = 32.063$ Mb/s. + 6.176 Mb/s. + 11.7 Mb/s.

$BW_{LI(n)} = 50$ Mb/s.

EI bandwidth is:

$$BW_{EI} = BW_{TEL} + BW_{ADP} + BW_{CH}$$

$$BW_{TEL} = 86.629 \text{ Mb/s.} \quad \text{(see e)}$$

$$BW_{ADP} = 24.904 \text{ Mb/s.} \quad \text{(see f)}$$

$$BW_{CH} = 19368 \times \frac{1}{1.675 \times 10^{-3} - 115.4 \times 10^{-6}} = 12.418 \text{ Mb/s}$$

$$BW_{EI} = 86.629 \text{ Mb/s.} + 24.904 \text{ Mb/s.} + 12.418 \text{ Mb/s.} = 123.951 \text{ Mb/s.}$$

5.3.1.8 Scenario h. Scenario h adds one Mb/s virtual bus with two members per LI.

LI bandwidth required is 51.038 Mb/s. EI bandwidth required is 125 Mb/s. Assumptions: Same as scenario g.

LI bandwidth is:

$$BW_{LI(n)} = BW_{TEL} + BW_{ADP} + BW_{CH} + BW_{VB}$$

$$BW_{TEL} + BW_{ADP} + BW_{CH} = 50 \text{ Mb/s.} \quad \text{(see g)}$$

$$BW_{VB} \text{ Message Rate: } \frac{1}{\frac{1024 \times 18}{1 \times 10^{-6}} - 55 \times 10^{-6}} = 54.41 \text{ M/s.}$$

$$BW_{VB} = 19080 \times 54.41 - 1{,}038 \text{ Mb/s.}$$

$$BW_{LI(n)} = 50 \text{ Mb/s.} + 1.038 \text{ Mb/s} = 51.038 \text{ Mb/s.}$$

EI bandwidth is:

$$BW_{EI} = BW_{TEL} + BW_{ADP} + BW_{CH} + BW_{VB}$$

$$BW_{TEL} + BW_{ADP} + BW_{CH} = 123.951 \text{ Mb/s.} \quad \text{(see g)}$$

$$BW_{VB} = 19368 \times \frac{1}{18.432 \times 10^{-3} = 115.4 \times 10^{-6}} = 1.057 \text{ Mb/s.}$$

$$BW_{EI} = 123.951 \text{ Mb/s} + 1.057 \text{ Mb/s} = 125 \text{ Mb/s.}$$

5.3.1.9 Scenario i. Scenario i adds one 5 Mb/s virtual bus with two members to each LI. Assumptions: Same as h. LI bandwidth required is 56.292 Mb/s. EI bandwidth required is 130.423 Mb/s.

LI bandwidth is:

$$BW_{LI(n)} = BW_{TEL} + BW_{ADP} + BW_{CH} + BW_{VB1} + BW_{VB2}$$

$BW_{TEL} + BW_{ADP} + BW_{CH} + BW_{VB1} = 51.038$ Mb/s. (see h)

BW_{VB2} Message Rate: 275.37 M/s.

$BW_{VB2} = 19080 \times 275.37 = 5.254$ Mb/s.

$BW_{LI(n)} = 51.038$ Mb/s + 5.254 Mb/s = 56.292 Mb/s.

EI bandwidth:

$$BW_{EI} = BW_{TEL} + BW_{ADP} + BW_{CH} + BW_{VB1} + BW_{VB2}$$

$BW_{TEL} + BW_{ADP} + BW_{CH} + BW_{VB1} = 125$ Mb/s (see h)

$BW_{VB2} = 19368 \times 280$ M/s = 5.423 Mb/s

$BW_{EI} = 125$ Mb/s + 5.423 Mb/s = 130.423 Mb/s

5.3.1.10 Scenario j. Scenario j adds one 10 Mb/s virtual bus with two members to each LI. Assumptions: Same as i. LI bandwidth required is 66.961 Mb/s. EI bandwidth required is 141.632 Mb/s.

LI bandiwdth is:

$$BW_{LI(n)} = BW_{TEL} = BW_{ADP} + BW_{CH} + BW_{VB1} + BW_{VB2} + BW_{VB3}$$

$BW_{TEL} + BW_{ADP} + BW_{CH} + BW_{VB1} + BW_{VB2} = 56.292$ Mb/s. (see i)

BW_{VB3} Message Rate: 559.22 M/s.

$BW_{VB3} = 19{,}080 \times 559.22 = 10.669$ Mb/s.

$BW_{LI(n)} = 56.292$ Mb/s + 10.669 Mb/s = 66.961 Mb/s.

EI bandwidth is:

$$BW_{EI} = BW_{TEL} + BW_{ADP} + BW_{CH} + BW_{VB1} + BW_{VB2} + BW_{VB3}$$

$$BW_{TEL} + BW_{ADP} + BW_{CH} + BW_{VB1} + BW_{VB2} = 130.423 \text{ Mb/s.} \quad \text{(see i)}$$

$$BW_{VB3} = 19,368 \times 578.77 \text{ M/s} = 11.209 \text{ Mb/s.}$$

$$BW_{EI} = 130.423 \text{ Mb/s} + 11.209 \text{ Mb/s} - 141.632 \text{ Mb/s.}$$

5.3.2 Significance of Bandwidth Determinations.

5.3.2.1 Blocked Traffic. Telephones and ADP devices are assumed to be off-hook 100% in all scenarios. This condition was mandated in the requirements. Since under these conditions the FI will not admit traffic onto the bus when capacity has been reached, any excess load offered to it will be blocked prior to accessing the system. The percent of subscribers blocked is the "percent blockage." This is not a probability of blockage in this case. The precent of subscribers blocked from the FI is shown in Table 5-3 for all scenarios. If necessary, it would be possible to determine the number of subscribers blocked by dividing the excess offered load by the bandwidth required per subscriber.

TABLE 5-3.
EXCESS OFFERED LOAD OVER FI CAPACITY (PERCENT BLOCKAGE) (FOR 1km EI).

LI/EI Rates (Assumed Capacity) mb/s		Offered Load mb/s	Scenario a	b	c	d	e	f	g	h	i	j
		LI	1.060	5.3	5.344	26.763	32.063	38.239	50	51.038	56.292	66.961
		1Km EI			6.597	64.971	86.629	111.533	123.951	125.0	130.423	141.632
1.	50	LI								2.03	11.17	25.32
	100	EI						10.34	19.32	20.0	23.32	29.39
2.	100	LI										
	50	EI				23.04	42.28	55.17	59.66	60.0	61.66	66.69
3.	100	LI										
	100	EI						10.34	19.32	20.0	23.32	29.39
4.	100	LI										
	200	EI										
5.	200	LI										
	100	EI						10.34	19.32	20.0	23.32	29.39
6.	200	LI										
	200	EI										

5.3.2.2 Bandwidth Usage Relationships. Message transferring functions on the FI can be expressed in terms of bandwidth required per message. These relationships provide a better understanding of the operation of the FI. Some functions are listed here:

LI:

1) Message processing time of 55 us requires about 30 Hz bandwidth per LIU transmission.

2) The polling operation to telephone users requires about 8 kb/s per poll.

3) Poll, query, and response requires about 18 kb/s per LIU transmission.

4) Each message requires about 1052 kb/s per LIU transmission.

5) The data portion of the message requires 1,024 kb/s per LI transmission.

EI:

1) Message processing time of 95 us requires about 116 Hz per EI transmission. This includes poll, query, and response processing time.

2) Propagation time for the poll, query, response, message interchange requires 25 Hz per interchange for a 1 km EI and 400 Hz for 16 km.

3) The polling operation to telephone users at an LICU requires about 10 kb/s per user. Where the user consists of one message generated by one LIU on the LI.

4) Poll, query, and response requires about 22 kb/s per user, or, message generated by one LIU.

5.3.2.3 Propogation Bandwidths on the EI. Propogation delays have been determined for the throughput model in 5.1 and calculated for all scenarios. Propogation times are interpreted here in terms of bandwidths. These bandwidths are minimal on the 1 km EI but become significant with the assumption of 8 km EI legs. Eight km legs require 16 km point-to-point transmission distances between EIUs.

A general expression has been developed for the bandwidth of the EI, BW_{EI}, in terms of the number of message-producing units, N_L, on the EI, i.e., the EIUs, the message rate, N_M, and the round trip propogation delay, D_n, for 1 km and 8 km legs.

$$BW_{EI} = \frac{N_L \, (N_M \; 19368)}{1 - N_L \, N_M \, (95 + D_n) \times 10^{-6}}$$

Where there are 19,368 bits in the poll, query, response and message transmissions, and 95 us processing time per message. This expression can be solved for N_L and the determination made of the number of users which the EI can accommodate for each of the bit rates given in the study requirements. This will show the limitations of the capability of the EI to support users separated by greater than normal distances. Assume:

1) All voice users N_M = 55.56 M/s.

2) BW_{EI}: a) 50 Mb/s.

b) 100 Mb/s.

c) 200 Mb/s.

3) $\tau = 5.1 \times 10^{-3}$ s/m.

4) D_8 = 326.4 us. for 8 km legs.

$$N_L = \frac{BW_{EI}}{N_M \, (19368) + BW_{EI} \, N_M \, (95 + 326.4) \text{ us}}$$

a) N_L = 22.25 @ 50 Mb/s.

b) N_L = 29.26 @ 100 Mb/s.

c) N_L = 34.73 @ 200 Mb/s.

and when D = 40.8 x 10^{-9} s for 1 km legs,

$$N_L = \frac{BW_{ET}}{N_M(19368) + BW_{ET}\ N_M(95.04)\ \mu s}$$

a) N_L = 46.26 @ 50 Mb/s

b) N_L = 95.97 @ 100 Mb/s

c) N_L = 182.0 @ 200 Mb/s

It is evident that the EI will support only a limited number of users on 8 km legs. An increase in 100 Mb/s accommodates only five more users on the 8 km EI. The mathematical limit, regardless of the bit rate, is about 52 users. In a reasonable scenario, there would probably be no need for more than a few users to be separated by that distance; possibly the radar, such as AN/TPS-43, and main ground-to-ground radio, such as AN/TRC-107. Propogation bandwidth required for, say, less than five 8 km legs would not be an excessive load on the EI if the other legs in the system were 1 km or less.

5.3.2.4 Information Throughput. The information throughput for each of the required scenarios has been calculated in Paragraph 5.1; however, it is informative to look at the amount of information which can be carried by the FI expressed in terms of bandwidth. This is in effect a statement of the efficiency of the FI.

A message carries 1,024 18-bit words of data. In one polling interval on the LI it takes 19,260 bits to transmit the message and 55 us of processing time. For the 1 km EI, these figures are 19,368 bits and 115.4 us of processing time. Virtual busses require only 19,080 bits on the EI and 19,152 bits on the EI per message. The polling interval is 18 ms for Com devices and 25 ms for ADP. With these facts taken into consideration, it can be determined that: Com traffic is 95.43% efficient on the LI and 94.56% efficient on the EI. ADP traffic is 95.49% efficient on the LI and 94.71% efficient on the EI. The differences between Com and ADP are due to different polling intervals which produce different total processing times. The differences between LI and EI are in the bits required for headers and in propogation delays. Since virtual busses do not use queuing and response, they are slightly more efficient than queuing response modes. Use of virtual busses for ADP increases efficiency for both Com and ADP to 96.6% and 96.24% for LI and EI, respectively.

These figures have been used in Table 5-4 to indicate information throughput in terms of bandwidth for pure Com or pure ADP point-to-point traffic. Mixtures of Com, ADP, virtual busses and other channels such as are in the scenarios of Paragraph 2.0 will give slightly different results.

TABLE 5-4. FI THROUGHPUT, mb/s.

	FI Capacities, mb/s					
	50		100		200	
	LI	EI (1km)	LI	EI (1km)	LI	EI (1km)
Com	47.71	47.28	95.43	95.56	190.86	189.12
ADP	47.74	47.35	95.49	94.71	190.98	189.42

Table 5-4 can be interpreted as the set traffic that can be carried over the FI for each of the FI bandwidths stated in the study requirements. For instance, a 50 Mb/s LI can carry 47.71 Mb/s of Com data. The other 2.29 Mb/s are used for overhead. If it is a telephone LI, it will support 372 full-duplex point-to-point circuits, i.e.,

$$\frac{47.71 \text{ Mb/s}}{2\text{x}64 \text{ kb/s}} = 372.$$

Or, a 50 Mb/s LI can carry 47.74 Mb/s of ADP data which will support 32 full-duplex 737.28 kb/s ADP channels. (737.28 kb/s is the rate corresponding to the 25 ms sample period given in the requirements for ADP traffic.)

5.4 Blockage Probabilities.

Two types of probabilities concerned with blocking of data throughput on the FI can be identified: 1) the probability that any packet will be blocked from being transmitted anywhere on the FI (P_{LIU}), and 2) the probability that at least one packet from an LI will be blocked from passing over the EI (P_{FI}). These probabilities have been determined separately for each scenario defined in Section 2.0. Refer to the end of this section for detailed calculations.

5.4.1 Blockage of Any Packet. The bit rates determined in Section 5.1.3 (Table 5-1) are used to calculate the probability of a packet sent from an LIU being blocked from going over the EI. These probabilities are summarized in Table 5-5.

Since the calculated required rates are lower than the available rates in scenarios a-d, no blockage occurs anywhere on the FI. In Scenario e, the same reasoning shows that there is no blockage on the LI at any of the designated rates or on the EI at 200 Mb/s. However, at 100 Mb/s on the EI for 16 km, the required rate exceeds the available rate. The probability of a message being blocked (P_{LIU}) must be determined.

TABLE 5-5. BLOCKAGE PROBABILITIES OF ANY PACKET ON FI

	LI (Mb/s)				EI (Mb/s)				
					1 km			16 km	
Scenario	50	100	200	50	100	200	50	100	200
a	0	0	0	-	-	-	-	-	-
b	0	0	0	-	-	-	-	-	-
c	0	0	0	0	0	0	0	0	0
d	0	0	0	0	0	0	0	0	0
e	0	0	0	0.456	0	0	0.555	0.110	0
f	0	0	0	0.573	0.147	0	0.640	0.280	0
g	0.202	0	0	0.769	0.538	0.076	0.810	0.619	0.238
h	0.215	0	0	0.770	0.540	0.081	0.811	0.621	0.241
i	0.274	0	0	0.776	0.551	0.102	0.814	0.628	0.257
j	0.631	0	0	0.786	0.571	0.143	0.822	0.643	0.287

If the maximum required transmission rate is m and the maximum allowed transmission rate is n, then each LIU has a n/m chance of transmitting over the EI. For example, since the maximum allowed rate is 100 Mb/s and the rate required to accommodate the traffic load is 112.39 Mb/s, the probability of a packet being transmitted over the EI is 100/112.39 = 0.89. Conversely, the packet has a 1 - 0.89 = 0.11 or 11% chance of being blocked from the EI.

5.4.2 Blockage of At Least One Packet. As determined in Section 5.4.1, no blocking occurs on the FI for scenarios a-d if all LIUs transfer packets over the EI. Starting with Scenario e, blockage begins to occur on the FI with all the LIUs transmitting on the EI. In a real situation, devices on the same LI will be communicating with each other as well as with devices on other LIs. A Monte Carlo method will be used to simulate this situation. This analysis will be concerned only with the probability that at least one packet from an LI will be blocked from being transmitted over the EI because, as seen in Section 5.4.1, this is where the majority of blocking occurs. Calculations follow this section.

5.4.2.1 Scenario e. One LIU has an equal probability of communicating with any other LIU on the FI, i.e., one Com LIU out of 80 Com LIUs has a 1/80 chance of communicating to another designated Com LIU. In this case, this implies that a Com LIU has a 10/80 or 1/8 probability of transmitting to a Com LIU on the same LI and a 70/80 or 7/8 probability of transmitting over the EI. A table of random numbers from 1 to 100 was used for this simulation. Each Com LIU was assigned a number from this table. If the value was 12.5 (1/8) or less, that Com LIU communicated only on the LI. A higher value meant that the Com LIU transmitted over the EI. Trials (120) were performed resulting in a mean of 8.9 Com LIUs per LI transmitting over the EI with a standard deviation of 0.8 over a normal distribution. To standardize a normal random variable, x, the expression $z = (x - \bar{x})/d$ is used. Z is the distance of x from its mean, $\bar{x}$, measured in units of standard deviations. As a result of this operation, z is a standardized, normally distributed random variable with a mean of zero and a standard deviation of one (see Figure 5-9).

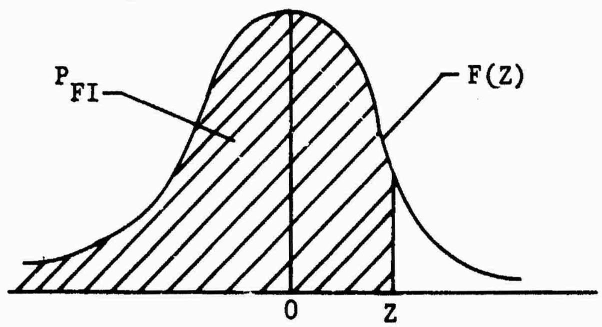

Figure 5-9.
The standardized normal distribution function.

From a table of cumulative normal probabilities can be determined the probability of blockage on the FI. This is done by letting x be the maximum number of LIUs/LI able to transmit over the EI. X is determined by multiplying the total number of LIUs on an LI by the ratio of the available transmission rate of the EI to the required transmission rate (as determined in Section 5.1.3). This ratio expresses the portion of the traffic load which can be accommodated by the FI, hence, the number of LIUs able to transmit over the EI.

As an example, consider the case of the 50 Mb/s, 1 km EI. The maximum number of LIUs/LI, x, to transmit on the EI is (10 LIUs) (50/91.977) = 5.44. From this, z = (8.9 - 5.44)/0.8 = 4.325. From a table of cumulative normal probabilities, the probability of x being greater than 5.44 (P_{FI}) is 0.99997. This same procedure is applied at the other rates and distance for the EI. The results are shown in Table 5-6.

TABLE 5-6. BLOCKAGE PROBABILITIES OF AT LEAST ONE PACKET ON FI.

	1 km EI (Mb/s)						16 km EI (Mb/s)					
	From 11 Mb/s Ch. LI			From Other LI			From 11 mb/s per Ch. LI			From Other LI		
Scenario	50	100	200	50	100	200	50	100	200	50	100	200
a	-	-	-	0	0	0	-	-	-	0	0	0
b	-	-	-	0	0	0	-	-	-	0	0	0
c	-	-	-	0	0	0	-	-	-	0	0	0
d	-	-	-	0	0	0	-	-	-	0	0	0
e	-	-	-	1.000	0	0	-	-	-	1.000	0.501	0
f	-	-	-	1.000	0.999	0	-	-	-	1.000	1.000	0
g	1.000	1.000	0.999	1.000	1.000	0.995	1.000	1.000	1.000	1.000	1.000	0.999
h	1.000	1.000	0.999	1.000	1.000	0.996	1.000	1.000	1.000	1.000	1.000	1.000
i	1.000	1.000	0.999	1.000	1.000	0.998	1.000	1.000	1.000	1.000	1.000	1.000
j	1.000	1.000	1.000	1.000	1.000	0.999	1.000	1.000	1.000	1.000	1.000	1.000

Throughout this analysis, calculations will be completed for the faster rates first. If the probability of blockage is 1 at a certain rate, it will be the same for slower rates under the same conditions.

5.4.2.2 Scenario f. Four ADP devices are added to each LI from Scenario e. Each ADP device has the same probability of transmitting on the EI as the Com devices have, i.e., 7/8 probability. A Monte Carlo simulation similar to that in scenario e was performed. The result was that the mean of the number of Com LIUs transmitting onto the EI remained at 8.9 while the mean for ADP LIUs is 3.5. The standard deviation is 0.866 for Com LIUs and 0.857 for ADP LIUs. The mean number of LIUs transmitting over the EI is the sum of the mean of Com and ADP LIUs while the total standard deviation is the square root of the sum of the squares of the individual standard deviations as seen in the calculations.

5.4.2.3 Scenario g. This scenario deviates from the others in that it has one LI contributing more to the traffic load on the EI than the other seven LIs. Since the 11 Mb/s channel transmits over the EI to the other LIs, the mean of the number of LIUs transmitting over the EI from the LI containing this channel increases by 1 while the mean for the other LIs remains the same. This causes a slight difference in the resulting blocking probabilities for each LI.

5.4.2.4 Scenarios h, i and j. The number of members belonging to the virtual bus is irrelevant here since only one member can transmit at any one time on the FI. The effect of the virtual bus is to decrease the amount of bandwidth available for other traffic. With each additional virtual bus, the effective EI bandwidth available for other traffic decreases.

Calculations: Throughput (T)

Scenario a

Com is on virtual bus.

$T = 18{,}000\ \mu s + 0.9258\ T_{PLI} + 18{,}936/BR_{LI} + 1.9258\ (18{,}000\ \mu s)$

$T_{PLI} = 18{,}000\ \mu s$

$T = 18{,}000 + 0.9258\ (18{,}000) + 18{,}936/BR_{LI} + 34{,}664.4$
$= 69{,}328.8 + 18{,}036/BR_{LI}$

50 Mb/s: T = 69.71 ms
100 Mb/s: T = 69.52 ms
200 Mb/s: T = 69.42 ms

Scenario b

$T = 18{,}000 + 0.9258\ T_{PLI} + 18{,}936/BR_{LI} + 1.9258\ T_{SI}$

$T_{PLI} = 18{,}000/5 = 3600 \qquad T_{SI} = 18{,}000$

$T = 18{,}000 + (0.9258)\ (3600) + 18{,}936/BR_{LI} + 34{,}664.4$

$= 55{,}997.28 + 18{,}936/BR_{LI}$

50 Mb/s: T = 56.03
100 Mb/s: T = 56.19
200 Mb/s: T = 56.09

Scenario c

T (LI only) = same as Scenario a

$T\ (FI) = 18{,}000 + (0.9258)\ (18{,}000) + 36/BR_{LI} + 55$
$+ 144/BR_{LI} + 37{,}872/BR_{LI} + 9000 + 0.9258\ T_{PEI}$
$+ 95 + 216/BR_{EI} + 3\ t_P + 18{,}972/BR_{EI} + t_P$
$+ (0.9258)\ (18{,}000) + 36/BR_{LI} + 55 + 144/BR_{LI}$
$+ 37{,}872/BR_{LI} + 1.9258\ T_{SI}$
$= 60{,}533.8 + 76{,}104/BR_{LI} + 0.9258\ T_{PEI}$
$+ 19{,}188/BR_{EI} + 4\ t_P + 1.9258\ T_{SI}$

$T_{PEI} = 18{,}000/3 = 6000 \qquad T_{SI} = 18{,}000$

$T = 60{,}533.8 + 76{,}104/BR_{LI} + (0.9258)\ (6000) + 19{,}188/BR_{EI} + 4\ t_P$
$+ 34{,}664.4 = 100{,}753 + 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\ t_P$

LI = 50 Mb/s; EI = 100 Mb/s: T = 102.49 ms (1 km)
= 102.79 ms (16 km)

LI = 100 Mb/s; EI = 50 Mb/s: T = 101.92 ms (1 km)
= 102.22 ms (16 km)

LI = 100 Mb/s; EI = 100 Mb/s: T = 101.73 ms (1 km)
= 102.03 ms (16 km)

LI = 100 Mb/s; EI = 200 Mb/s: T = 101.63 ms (1 km)
= 101.94 ms (16 km)

LI = 200 Mb/s; EI = 100 Mb/s: T = 101.54 ms (1 km)
= 101.65 ms (16 km)

LI = 200 Mb/s; EI = 200 Mb/s: T = 101.25 ms (1 km)
= 101.56 ms (16 km)

Scenario d

T (LI only) = same as Scenario b

$$T\ (FI) = 18{,}000 + (0.9258)\ (3600) + 55 + 9000 + 0.9258\ T_{PEI} + 95 + (0.9258)\ (3600) + 55 + 1.9258\ T_{SI} + 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\ t_p$$

T_{PEI} = 3600/3 = 1200 T_{SI} = 18,000

$$T = 69{,}646.12 + 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\ t_p$$

LI = 50 Mb/s; EI = 100 Mb/s: T = 71.38 (1 km)
= 71.69 (16 km)

LI = 100 Mb/s; EI = 50 Mb/s: T = 70.81 (1 km)
= 71.12 (16 km)

LI = 100 Mb/s; EI = 100 Mb/s: T = 70.62 (1 km)
= 70.93 (16 km)

LI = 100 Mb/s; EI = 200 Mb/s: T = 70.52 (1 km)
= 70.83 (16 km)

LI = 200 Mb/s; EI = 100 Mb/s: T = 70.24 (1 km)
= 70.54 (16 km)

LI = 200 Mb/s; EI = 200 Mb/s: T = 70.14 (1 km)
= 70.45 (16 km)

Scenario e

$$T\ (\text{LI only}) = 18{,}000 + (0.9258)\ (18{,}000/10) + 18{,}936/BR_{LI}$$
$$+ 1.9258\ (18{,}000) = 54{,}330.84 + 18{,}936/BR_{LI}$$

50 Mb/s: $T = 54.71$
100 Mb/s: $T = 54.52$
200 Mb/s: $T = 54.43$

$$T\ (\text{FI}) = 18{,}000 + (0.9258)\ (1800) + 55 + 9000$$
$$+ 0.9258\ (1800/8) + 95 + 0.9258\ (1800) + 55$$
$$+ 1.9258\ (18{,}000) + 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\ t_p$$

LI = 50 Mb/s; EI = 100 Mb/s: $T = 67.14$ (1 km)
$= 67.45$ (16 km)

LI = 100 Mb/s; EI = 50 Mb/s: $T = 66.58$ (1 km)
$= 66.88$ (16 km)

LI = 100 Mb/s; EI = 100 Mb/s: $T = 66.38$ (1 km)
$= 66.69$ (16 km)

LI = 100 Mb/s; EI = 200 Mb/s: $T = 66.29$ (1 km)
$= 66.59$ (16 km)

LI = 200 Mb/s; EI = 100 Mb/s: $T = 66.00$ (1 km)
$= 66.31$ (16 km)

LI = 200 Mb/s; EI = 200 Mb/s: $T = 65.91$ (1 km)
$= 66.21$ (16 km)

Scenario f

$$T\ (\text{LI only, Com}) = 18{,}000 + 0.9258\ T_{PLI} + 18{,}936/BR_{LI}$$
$$+ 1.9258\ (18{,}000)$$

$$T_{PLI} = 1/(10/18{,}000 + 4/25{,}000) = 1398$$

$$T = 54{,}062.4 + 18{,}936/BR_{LI}$$

50 Mb/s: $T = 54.44$
100 Mb/s: $T = 54.25$
200 Mb/s: $T = 54.16$

$$T\ (\text{LI only, ADP}) = 25{,}000 + 0.9258\ (1398) + 36/BR_{LI}$$
$$+ 55 + 144/BR_{LI} + 18{,}936/BR_{LI} + 1.9258\ (25{,}000)$$
$$= 74{,}494.268 + 19{,}116/BR_{LI}$$

50 Mb/s: $T = 74.88$
100 Mb/s: $T = 74.69$
200 Mb/s: $T = 74.59$

$$T\ (FI,\ Com) = 18{,}000 + 0.9258\ (1398) + 55 + 9000 + 0.9258\ T_{PEI}$$
$$+ 95 + 0.9258\ (1398) + 55 + 1.9258\ (18{,}000)$$
$$+ 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\ t_p$$

$$T_{PEI} = 1398/8 = 174.69$$

$$T = 64{,}619.665 + 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\ t_p$$

LI = 50 Mb/s; EI = 100 Mb/s: T = 66.35 (1 km)
= 66.66 (16 km)

LI = 100 Mb/s; EI = 50 Mb/s: T = 65.78 (1 km)
= 66.09 (16 km)

LI = 100 Mb/s; EI = 100 Mb/s: T = 65.59 (1 km)
= 65.90 (16 km)

LI = 100 Mb/s; EI = 200 Mb/s: T = 65.49 (1 km)
= 65.80 (16 km)

LI = 200 Mb/s; EI = 100 Mb/s: T = 65.21 (1 km)
= 65.52 (16 km)

LI = 200 Mb/s; EI = 200 Mb/s: T = 65.11 (1 km)
= 65.42 (16 km)

$$T\ (FI,\ ADP) = 25{,}000 + 0.9258\ (1398) + 55 + 12{,}500 + 0.9258\ (174.69)$$
$$+ 95 + 0.9258\ (1398) + 55 + 1.9258\ (25{,}000) + 76{,}104/BR_{LI}$$
$$+ 19{,}188/BR_{EI} + 4\ t_p = 88{,}600.265 + 76{,}104/BR_{LI}$$
$$+ 19{,}188/BR_{EI} + 4\ t_p$$

LI = 50 Mb/s; EI = 100 Mb/s: T = 90.33 (1 km)
= 90.64 (16 km)

LI = 100 Mb/s; EI = 50 Mb/s: T = 89.77 (1 km)
= 90.07 (16 km)

LI = 100 Mb/s; EI = 100 Mb/s: T = 89.57 (1 km)
= 89.88 (16 km)

LI = 100 Mb/s; EI = 200 Mb/s: T = 89.48 (1 km)
= 89.78 (16 km)

LI = 200 Mb/s; EI = 100 Mb/s: T = 89.19 (1 km)
89.50 (16 km)

LI = 200 Mb/s; EI = 200 Mb/s: T = 89.10 (1 km)
= 89.40 (16 km)

Scenario g

For 11 Mb/s channel LI:

T (LI only, 11 Mb/s ch) = $210 + 0.9258\ T_{PLI} + 18{,}936/BR_{LI} + 1.9258\ (210)$

$T_{PLI} = 1/(10/18{,}000 + 4/25{,}000 + 1/210) = 182.566$

$T = 783.44 + 18{,}936/BR_{LI}$

50 Mb/s: $T = 1.162$
100 Mb/s: $T = 0.973$
200 Mb/s: $T = 0.878$

T (LI only, Com) = $18{,}000 + 0.9258\ (182.566)$
$+ 18{,}936/BR_{LI} + 1.9258\ (18{,}000)$
$= 52{,}833.42 + 18{,}936/BR_{LI}$

50 Mb/s: $T = 53.21$
100 Mb/s: $T = 53.02$
200 Mb/s: $T = 52.93$

T (LI only, ADP) = $25{,}000 + 0.9258\ (182.566) + 18{,}936/BR_{LI}$
$+ 1.9258\ (25{,}000) = 73{,}314.02 + 18{,}936/BR_{LI}$

50 Mb/s: $T = 73.69$
100 Mb/s: $T = 73.50$
200 Mb/s: $T = 73.40$

T (FI, 11 Mb/s ch) = $210 + 0.9258\ (182.566) + 55 + 0.5\ (210)$
$+ 0.9258\ T_{PEI} + 95 + 0.9258\ (1398) + 55 + 1.9258\ (210)$
$+ 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\ t_p$

$T_{PEI} = 1/(80/18{,}000 + 32/25{,}000 + 1/210) = 95.36$

$T = 2475.99 + 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\ t_p$

LI = 50 Mb/s; EI = 100 Mb/s: $T = 4.21$ (1 km)
$= 4.52$ (16 km)

LI = 100 Mb/s; EI = 50 Mb/s: $T = 3.64$ (1 km)
$= 3.95$ (16 km)

LI = 100 Mb/s; EI = 100 Mb/s: $T = 3.45$ (1 km)
$= 3.76$ (16 km)

LI = 100 Mb/s; EI = 200 Mb/s: $T = 3.35$ (1 km)
$= 3.66$ (16 km)

LI = 200 Mb/s; EI = 100 Mb/s: $T = 3.07$ (1 km)
$= 3.37$ (16 km)

LI = 200 Mb/s; EI = 200 Mb/s: $T = 2.97$ (1 km)
$= 3.28$ (16 km)

$$
\begin{aligned}
T\ (FI,\ Com) &= 18{,}000 + 0.9258\ (182.566) + 55 + 9000 \\
&+ 0.9258\ (95.36) + 95 + 0.9258\ (1398) + 55 + 1.9258\ (18{,}000) \\
&+ 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\ t_p \\
&= 63{,}420.972 + 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\ t_p
\end{aligned}
$$

LI = 50 Mb/s; EI = 100 Mb/s: T = 65.16 (1 km)
= 65.46 (16 km)

LI = 100 Mb/s; EI = 50 Mb/s: T = 64.59 (1 km)
= 64.89 (16 km)

LI = 100 Mb/s; EI = 100 Mb/s: T = 64.40 (1 km)
= 64.70 (16 km)

LI = 100 Mb/s; EI = 200 Mb/s: T = 64.30 (1 km)
= 64.61 (16 km)

LI = 200 Mb/s; EI = 100 Mb/s: T = 64.01 (1 km)
= 64.32 (16 km)

LI = 200 Mb/s; EI = 200 Mb/s: T = 63.92 (1 km)
= 64.22 (16 km)

$$
\begin{aligned}
T\ (FI,\ ADP) &= 25{,}000 + 0.9258\ (182.566) + 55 + 12{,}500 + 0.9258\ (95.36) \\
&+ 95 + 0.9258\ (1398) + 55 + 1.9258\ (25{,}000) \\
&+ 76{,}104/BR_{LI} + 19{,}188/BR_{EI} \\
&+ 4\ t_p = 87{,}401.572 + 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\ t_p
\end{aligned}
$$

LI = 50 Mb/s; EI = 100 Mb/s: T = 89.14 (1 km)
= 89.44 (16 km)

LI = 100 Mb/s; EI = 50 Mb/s: T = 88.57 (1 km)
88.80 (16 km)

LI = 100 Mb/s; EI = 100 Mb/s: T = 88.38 (1 km)
= 88.68 (16 km)

LI = 100 Mb/s; EI = 200 Mb/s: T = 88.28 (1 km)
= 88.59 (16 km)

LI = 200 Mb/s; EI = 100 Mb/s: T = 88.00 (1 km)
= 88.30 (16 km)

LI = 200 Mb/s; EI = 200 Mb/s: T = 87.90 (1 km)
= 88.21 (16 km)

For other LIs:

T (LI only, Com) = same as Scenario f.

T (LI only, ADP) = same as Scenario f.

$$
\begin{aligned}
T\ (FI,\ Com) &= 18{,}000 + 0.9258\ (1398) + 55 + 9000 + 0.9258\ (95.36) \\
&+ 95 + 0.9258\ (1398) + 55 + 1.9258\ (18{,}000) + 76{,}104/BR_{LI} \\
&+ 19{,}188/BR_{EI} + 4\ t_p = 64{,}546.221 + 76{,}104/BR_{LI} \\
&+ 19{,}188/BR_{EI} + 4\ t_p
\end{aligned}
$$

LI = 50 Mb/s; EI = 100 Mb/s: T = 66.28 (1 km)
= 66.59 (16 km)

LI = 100 Mb/s; EI = 50 Mb/s: T = 65.71 (1 km)
= 66.02 (16 km)

LI = 100 Mb/s; EI = 100 Mb/s: T = 65.52 (1 km)
= 65.83 (16 km)

LI = 100 Mb/s; EI = 200 Mb/s: T = 65.42 (1 km)
= 65.73 (16 km)

LI = 200 Mb/s; EI = 100 Mb/s: T = 65.14 (1 km)
= 65.45 (16 km)

LI = 200 Mb/s; EI = 200 Mb/s: T = 65.04 (1 km)
= 65.35 (16 km)

$$
\begin{aligned}
T\ (FI,\ ADP) &= 25{,}000 + 0.9258\ (1398) + 55 + 12{,}500 + 0.9258\ (95.36) \\
&\quad + 95 + 0.9258\ (1398) + 55 + 1.9258\ (25{,}000) \\
&\quad + 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\ t_p \\
&= 88{,}526.821 + 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\ t_p
\end{aligned}
$$

LI = 50 Mb/s; EI = 100 Mb/s: T = 90.26 (1 km)
= 90.57 (16 km)

LI = 100 Mb/s; EI = 50 Mb/s: T = 89.69 (1 km)
= 90.00 (16 km)

LI = 100 Mb/s; EI = 100 Mb/s: T = 89.50 (1 km)
= 89.81 (16 km)

LI = 100 Mb/s; EI = 200 Mb/s: T = 89.40 (1 km)
= 89.71 (16 km)

LI = 200 Mb/s; EI = 100 Mb/s: T = 89.12 (1 km)
= 89.43 (16 km)

LI = 200 Mb/s; EI = 200 Mb/s: T = 89.02 (1 km)
= 89.33 (16 km)

<u>Scenario h</u>

For 11 Mb/s channel LI:

$$T\ (\text{LI only, 1 Mb/s VB}) = 1 + 0.9258\ T_{PLI} + 18{,}936/BR_{LI} + 1.9258\ T_{SI}$$

$$T_{PLI} = 1/(10/18{,}000 + 4/25{,}000 + 2/210) = 97.66$$

$$T_{SI} = 210$$

$$T = 495.83 + 18{,}936/BR_{LI}$$

50 Mb/s: T = 0.875
100 Mb/s: T = 0.685
200 Mb/s: T = 0.591

$$T\ (\text{LI only, 11 Mb/s ch}) = 210 + 0.9258\ (97.66) + 18{,}936/BR_{LI} + 1.9258\ (210) = 704.83 + 18{,}936/BR_{LI}$$

50 Mb/s: T = 1.08
100 Mb/s: T = 0.89
200 Mb/s: T = 0.80

$$T\ (\text{LI only, Com}) = 18{,}000 + 0.9258\ (97.66) + 18{,}936/BR_{LI} + 1.9258\ (18{,}000) = 52{,}754.8 + 18{,}936/BR_{LI}$$

50 Mb/s: T = 53.13
100 Mb/s: T = 52.94
200 Mb/s: T = 52.85

$$T\ (\text{LI only, ADP}) = 25{,}000 + 0.9258\ (97.66) + 18{,}936/BR_{LI} + 1.9258\ (25{,}000) = 73{,}235.4 + 18{,}936/BR_{LI}$$

50 Mb/s: T = 73.61
100 Mb/s: T = 73.42
200 Mb/s: T = 73.32

$$T\ (\text{FI, 1 Mb/s VB}) = 1 + 0.9258\ (97.66) + 0.5 + 0.9258\ T_{PEI} + 0.9258\ T_{PLI} + 1.9258\ (210) + 37{,}872/BR_{LI} + 180/BR_{EI} + 2\ t_p + 18{,}972/BR_{EI} + 37{,}872/BR_{LI}$$

$$T_{PLI} = 1/(10/18{,}000 + 4/25{,}000 + 1/210) = 182.566$$

$$T_{PEI} = 1/(80/18{,}000 + 32/25{,}000 + 1/210 + 1/18{,}936) = 94.88$$

$$T = 349.178 + 75{,}744/BR_{LI} + 19{,}152/BR_{EI} + 2\ t_p$$

LI = 50 Mb/s; EI = 100 Mb/s: T = 2.07 (1 km)
= 2.22 (16 km)

LI = 100 Mb/s; EI = 50 Mb/s: T = 1.50 (1 km)
= 1.65 (16 km)

LI = 100 Mb/s; EI = 100 Mb/s: T = 1.31 (1 km)
= 1.46 (16 km)

LI = 100 Mb/s; EI = 200 Mb/s: T = 1.21 (1 km)
= 1.37 (16 km)

LI = 200 Mb/s; EI = 100 Mb/s: T = 0.93 (1 km)
= 1.08 (16 km)

LI = 200 Mb/s; EI = 200 Mb/s: T = 0.83 (1 km)
= 0.99 (16 km)

$$T\,(\text{FI, 11 Mb/s ch}) = 210 + 0.9258\,(97.66) + 55 + 0.5\,(210) + 0.9258\,(94.88) + 95 + 0.9258\,(182.566) + 55 + 1.9258\,(210) + 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\,t_p$$

$$= 1271.69 + 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\,t_p$$

LI = 50 Mb/s; EI = 100 Mb/s: T = 3.01 (1 km)
= 3.32 (16 km)

LI = 100 Mb/s; EI = 50 Mb/s: T = 2.44 (1 km)
= 2.75 (16 km)

LI = 100 Mb/s; EI = 100 Mb/s: T = 2.25 (1 km)
= 2.56 (16 km)

LI = 100 Mb/s; EI = 200 Mb/s: T = 2.15 (1 km)
= 2.46 (16 km)

LI = 200 Mb/s; EI = 100 Mb/s: T = 1.87 (1 km)
= 2.17 (16 km)

LI = 200 Mb/s; EI = 200 Mb/s: T = 1.77 (1 km)
= 2.08 (16 km)

$$T\,(\text{FI, Com}) = 18{,}000 + 0.9258\,(97.66) + 55 + 9000 + 0.9258\,(94.88) + 95 + 0.9258\,(182.566) + 55 + 1.9258\,(18{,}000) + 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\,t_p$$

$$= 62{,}216.673 + 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\,t_p$$

LI = 50 Mb/s; EI = 100 Mb/s: T = 63.95 (1 km)
= 64.26 (16 km)

LI = 100 Mb/s; EI = 50 Mb/s: T = 63.38 (1 km)
= 63.69 (16 km)

LI = 100 Mb/s; EI = 100 Mb/s: T = 63.19 (1 km)
= 63.50 (16 km)

LI = 100 Mb/s; EI = 200 Mb/s: T = 63.09 (1 km)
= 63.40 (16 km)

LI = 200 Mb/s; EI = 100 Mb/s: T = 62.81 (1 km)
= 63.12 (16 km)

LI = 200 Mb/s; EI = 200 Mb/s: T = 62.71 (1 km)
= 63.02 (16 km)

$$T\,(\text{FI, ADP}) = 25{,}000 + 0.9258\,(97.66) + 55 + 12{,}500 + 0.9258\,(94.88) + 76{,}104/BR_{LI} + 95 + 0.9258\,(182.566) + 55 + 1.9258\,(25{,}000) + 19{,}188/BR_{EI} + 4\,t_p = 86{,}197.273 + 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\,t_p$$

LI = 50 Mb/s; EI = 100 Mb/s: T = 87.93 (1 km)
= 88.24 (16 km)

LI = 100 Mb/s; EI = 50 Mb/s: T = 87.36 (1 km)
= 87.67 (16 km)

LI = 100 Mb/s; EI = 100 Mb/s: T = 87.17 (1 km)
= 87.48 (16 km)

LI = 100 Mb/s; EI = 200 Mb/s: T = 87.07 (1 km)
= 87.58 (16 km

LI = 200 Mb/s; EI = 100 Mb/s: T = 86.79 (1 km)
= 87.10 (16 km)

LI = 200 Mb/s; EI = 200 Mb/s: T = 86.69 (1 km)
= 87.00 (16 km)

For other LIs:

$$T\ (\text{LI only, 1 Mb/s VB}) = 1 + 0.9258\ T_{PLI} + 18{,}936/BR_{LI} + 1.9258\ (210)$$

$$T_{PLI} = 1/(10/18{,}000 + 4/25{,}000 + 1/210) = 182.566$$

$$T = 574.4376 + 18{,}936/BR_{LI}$$

50 Mb/s: T = 0.95
100 Mb/s: T = 0.76
200 Mb/s: T = 0.67

T (LI only, Com) = same as for 11 Mb/s channel LI, Scenario g.

T (LI only, ADP) = ame as for 11 Mb/s channel LI, Scenario g.

$$\begin{aligned} T\ (\text{FI, 1 Mb/s VB}) &= 1 + 0.9258\ (182.566) + 0.5 \\ &\quad + 0.9258\ (94.88) + 0.9258\ (182.566) + 1.9258\ (210) \\ &\quad + 75{,}744/BR_{LI} + 19{,}152/BR_{EI} + 2\ t_p \\ &= 831.79711 + 75{,}744/BR_{LI} + 19{,}152/BR_{EI} + 2\ t_p \end{aligned}$$

LI = 50 Mb/s; EI = 100 Mb/s: T = 2.55 (1 km)
= 2.70 (16 km)

LI = 100 Mb/s; EI = 50 Mb/s: T = 1.98 (1 km)
= 2.13 (16 km)

LI = 100 Mb/s; EI = 100 Mb/s: T = 1.79 (1 km)
= 1.94 (16 km)

LI = 100 Mb/s; EI = 200 Mb/s: T = 1.69 (1 km)
= 1.85 (16 km)

LI = 200 Mb/s; EI = 100 Mb/s: T = 1.41 (1 km)
= 1.56 (16 km)

LI = 200 Mb/s; EI = 200 Mb/s: T = 1.31 (1 km)
= 1.47 (16 km)

$$T\ (FI,\ Com) = 18{,}000 + 0.9258\ (182.566) + 55 + 9000 + 0.9258\ (94.88) + 95 + 0.9258\ (182.566) + 55 + 1.9258\ (18{,}000) + 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\ t_p$$

$$= 62{,}296.279 + 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\ t_p$$

LI = 50 Mb/s; EI = 100 Mb/s: T = 64.03 (1 km)
= 64.34 (16 km)

LI = 100 Mb/s; EI = 50 Mb/s: T = 63.46 (1 km)
= 63.77 (16 km)

LI = 100 Mb/s; EI = 100 Mb/s: T = 63.27 (1 km)
= 63.58 (16 km)

LI = 100 Mb/s; EI = 200 Mb/s: T = 63.17 (1 km)
= 63.48 (16 km)

LI = 200 Mb/s; EI = 100 Mb/s: T = 62.89 (1 km)
= 63.20 (16 km)

LI = 200 Mb/s; EI = 200 Mb/s: T = 62.79 (1 km)
= 63.10 (16 km)

$$T\ (FI,\ ADP) = 25{,}000 + 0.9258\ (182.566) + 55 + 12{,}500 + 0.9258\ (94.88) + 95 + 0.9258\ (182.566) + 55 + 1.9258\ (25{,}000) + 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\ t_p$$

$$= 86{,}275.879 + 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\ t_p$$

LI = 50 Mb/s; EI = 100 Mb/s: T = 88.01 (1 km)
= 88.32 (16 km)

LI = 100 Mb/s; EI = 50 Mb/s: T = 87.44 (1 km)
= 87.75 (16 km)

LI = 100 Mb/s; EI = 100 Mb/s: T = 87.25 (1 km)
= 87.56 (16 km)

LI = 100 Mb/s; EI = 200 Mb/s: T = 87.15 (1 km)
= 87.46 (16 km)

LI = 200 Mb/s; EI = 100 Mb/s: T = 86.87 (1 km)
= 87.18 (16 km)

LI = 200 Mb/s; EI = 200 Mb/s: T = 86.77 (1 km)
= 87.08 (16 km)

Scenario i

For 11 Mb/s channel LI:

$$T \text{ (LI only, 5 Mb/s VB)} = 0.2 + 0.9258\, T_{PLI} + 18{,}936/BR_{LI} + 1.9258\,(210)$$

$$T_{PLI} = 1/(10/18{,}000 + 4/25{,}000 + 3/210) = 66.66$$

$$T = 466.33 + 18{,}936/BR_{LI}$$

50 Mb/s: T = 0.85
100 Mb/s: T = 0.66
200 Mb/s: T = 0.56

T (LI only, 1 Mb/s VB) = same as for 5 Mb/s VB

$$T \text{ (LI only, 11 Mb/s ch)} = 210 + 0.9258\,(66.66) + 18{,}936/BR_{LI} + 1.9258\,(210) = 676.13 + 18{,}936/BR_{LI}$$

50 Mb/s: T = 1.05
100 Mb/s: T = 0.87
200 Mb/s: T = 0.77

$$T \text{ (LI only, Com)} = 18{,}000 + 0.9258\,(66.66) + 18{,}936/BR_{LI} + 1.9258\,(18{,}000) = 52{,}726.114 + 18{,}936/BR_{LI}$$

50 Mb/s: T = 53.10
100 Mb/s: T = 52.92
200 Mb/s: T = 52.82

$$T \text{ (LI only, ADP)} = 25{,}000 + 0.9258\,(66.66) + 18{,}936/BR_{LI} + 1.9258\,(25{,}000) = 73{,}206.714 + 18{,}936/BR_{LI}$$

50 Mb/s: T = 73.59
100 Mb/s: T = 73.40
200 Mb/s: T = 73.30

$$T \text{ (FI, 5 Mb/s VB)} = 0.2 + 0.9258\,(66.66) + 0.5\,(0.2) + 0.9258\,T_{PEI} + 0.9258\,(T_{PLI}) + 1.9258\,(210) + 75{,}744/BR_{LI} + 19{,}152/BR_{EI} + 2\,t_p$$

$$T_{PLI} = 1/(10/18{,}000 + 4/25{,}000 + 2/210) = 97.66$$

$$T_{PEI} = 1/(80/18{,}000 + 32/25{,}000 + 1/210 + 1/18{,}936 + 1/3787.2) = 92.565$$

$$T = 642.528 + 75{,}744/BR_{LI} + 19{,}152/BR_{EI} + 2\,t_p$$

LI = 50 Mb/s; EI = 100 Mb/s: T = 2.71 (1 km)
+ 2.86 (16 km)

LI = 100 Mb/s; EI = 50 Mb/s: T = 2.14 (1 km)
= 2.29 (16 km)

LI = 100 Mb/s; EI = 100 Mb/s: T = 1.95 (1 km)
= 2.10 (16 km)

LI = 100 Mb/s; EI = 200 Mb/s: T = 1.85 (1 km)
= 2.01 (16 km)

LI = 200 Mb/s; EI = 100 Mb/s: T = 1.57 (1 km)
= 1.72 (16 km)

LI = 200 Mb/s; EI = 200 Mb/s: T = 1.47 (1 km)
= 1.63 (16 km)

T (FI, 1 Mb/s VB) = same as for 5 Mb/s VB

$$
\begin{aligned}
T\ (\text{FI, 11 Mb/s ch}) &= 210 + 0.9258\ (66.66) + 55 + 0.5\ (210) \\
&\quad + 0.9258\ (92.565) + 95 + 0.9258\ (97.66) + 55 \\
&\quad + 1.9258\ (210) + 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\ t_p \\
&= 1162.2421 + 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\ t_p
\end{aligned}
$$

LI = 50 Mb/s; EI = 100 Mb/s: T = 2.90 (1 km)
= 3.21 (16 km)

LI = 100 Mb/s; EI = 50 Mb/s: T = 2.33 (1 km)
= 2.64 (16 km)

LI = 100 Mb/s; EI = 100 Mb/s: T = 2.14 (1 km)
= 2.45 (16 km)

LI = 100 Mb/s; EI = 200 Mb/s: T = 2.04 (1 km)
= 2.35 (16 km)

LI = 200 Mb/s; EI = 100 Mb/s: T = 1.76 (1 km)
= 2.06 (16 km)

LI = 200 Mb/s; EI = 200 Mb/s: T = 1.66 (1 km)
= 1.97 (16 km)

$$
\begin{aligned}
T\ (\text{FI, Com}) &= 18{,}000 + 0.9258\ (66.66) + 55 + 9000 \\
&\quad + 0.9258\ (92.565) + 95 + 0.9258\ (97.66) + 55 \\
&\quad + 1.9258\ (18{,}000) + 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\ t_p \\
&= 62{,}107.224 + 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\ t_p
\end{aligned}
$$

LI = 50 Mb/s; EI = 100 Mb/s: T = 63.84 (1 km)
= 64.15 (16 km)

LI = 100 Mb/s; EI = 50 Mb/s: T = 63.27 (1 km)
= 63.58 (16 km)

LI = 100 Mb/a; EI = 100 Mb/s: T = 63.08 (1 km)
63.39 (16 km)

LI = 100 Mb/s; EI = 200 Mb/s: T = 62.98 (1 km)
= 63.29 (16 km)

LI = 200 Mb/s; EI = 100 Mb/s: T = 63.70 (1 km)
= 63.01 (16 km)

LI = 200 Mb/s; EI = 200 Mb/s: T = 62.60 (1 km)
= 62.91 (16 km)

$$\begin{aligned} T\ (\text{FI, ADP}) &= 25{,}000 + 0.9258\ (66.66) + 55 + 12{,}500 \\ &\quad + 0.9258\ (92.565) + 95 + 0.9258\ (97.66) + 55 + 1.9258\ (25{,}000) \\ &\quad + 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\ t_p \\ &= 86{,}087.824 + 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\ t_p \end{aligned}$$

LI = 50 Mb/s; EI = 100 Mb/s: T = 87.82 (1 km)
= 88.13 (16 km)

LI = 100 Mb/s; EI = 50 Mb/s: T = 87.25 (1 km)
= 87.56 (16 km)

LI = 100 Mb/s; EI = 100 Mb/s: T = 87.06 (1 km)
= 87.34 (16 km)

LI = 100 Mb/s; EI = 200 Mb/s: T = 86.96 (1 km)
= 87.28 (16 km)

LI = 200 Mb/s; EI = 100 Mb/s: T = 86.68 (1 km)
= 86.99 (16 km)

LI = 200 Mb/s; EI = 200 Mb/s: T = 86.58 (1 km)
= 86.89 (16 km)

For other LIs:

T (LI only, 5 Mb/s VB) = same as for 1 Mb/s VB on 11 Mb/s ch LI in Scenario h.

T (LI only, 1 Mb/s VB) = same as for 5 Mb/s VB

T (LI only, Com) = same as for Com on 11 Mb/s ch LI in Scenario h.

T (LI only, ADP) = same as for ADP on 11 Mb/s ch LI in Scenario h.

$$\begin{aligned} T\ (\text{FI, 5 Mb/s VB}) &= 0.2 + 0.9258\ (97.66) + 0.5\ (0.2) \\ &\quad + 0.9258\ (92.565) + 0.9258\ (97.66) + 1.9258\ (210) \\ &\quad + 75{,}744/BR_{LI} + 19{,}152/BR_{EI} + 2\ t_p \\ &= 671.24 + 75{,}744/BR_{LI} + 19{,}152/BR_{EI} + 2\ t_p \end{aligned}$$

LI = 50 Mb/s; EI = 100 Mb/s: T = 2.74 (1 km)
= 2.89 (16 km)

LI = 100 Mb/s; EI = 50 Mb/s: T = 2.17 (1 km)
= 2.32 (16 km)

LI = 100 Mb/s; EI = 100 Mb/s: T = 1.98 (1 km)
= 2.13 (16 km)

LI = 100 Mb/s; EI = 200 Mb/s: T = 1.88 (1 km)
= 2.04 (16 km)

LI = 200 Mb/s; EI = 100 Mb/s: T = 1.60 (1 km)
= 1.75 (16 km)

LI = 200 Mb/s; EI = 200 Mb/s: T = 1.50 (1 km)
= 1.66 (16 km)

T (FI, 1 Mb/s VB) = same as for 5 Mb/s VB

$$
\begin{aligned}
T\ (\text{FI, Com}) &= 18{,}000 + 0.9258\ (97.66) + 55 + 9000 \\
&+ 0.9258\ (92.565) + 95 + 0.9258\ (97.66) + 55 \\
&+ 1.9258\ (18{,}000) + 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\ t_p \\
&= 62{,}135.924 + 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\ t_p
\end{aligned}
$$

LI = 50 Mb/s; EI = 100 Mb/s: T = 63.87 (1 km)
= 64.18 (16 km)

LI = 100 Mb/s; EI = 50 Mb/s: T = 63.30 (1 km)
= 63.61 (16 km)

LI = 100 Mb/s; EI = 100 Mb/s: T = 63.11 (1 km)
= 63.42 (16 km)

LI = 100 Mb/s; EI = 200 Mb/s: T = 63.01 (1 km)
= 63.32 (16 km)

LI = 200 Mb/s; EI = 100 Mb/s: T = 63.73 (1 km)
= 63.04 (16 km)

LI = 200 Mb/s; EI = 200 Mb/s: T = 62.63 (1 km)
= 62.74 (16 km)

$$
\begin{aligned}
T\ (\text{FI, ADP}) &= 25{,}000 + 0.9258\ (97.66) + 55 + 12{,}500 + 0.9258\ (92.565) \\
&+ 95 + 0.9258\ (97.66) + 55 + 1.9258\ (25{,}000) + 76{,}104/BR_{LI} \\
&+ 19{,}188/BR_{EI} + 4\ t_p = 86{,}116.524 + 76{,}104/BR_{LI} \\
&+ 19{,}188/BR_{EI} + 4\ t_p
\end{aligned}
$$

LI = 50 Mb/s; EI = 100 Mb/s: T = 87.85 (1 km)
= 88.16 (16 km)

LI = 100 Mb/s; EI = 50 Mb/s: T = 87.28 (1 km)
= 87.59 (16 km)

LI = 100 Mb/s; EI = 100 Mb/s: T = 87.09 (1 km)
= 87.37 (16 km)

LI = 100 Mb/s; EI = 200 Mb/s: T = 86.99 (1 km)
= 87.31 (16 km)

LI = 200 Mb/s; EI = 100 Mb/s: T = 86.71 (1 km)
= 87.02 (16 km)

LI = 200 Mb/s; EI = 200 Mb/s: T = 86.61 (1 km)
= 86.92 (16 km)

Scenario j

For 11 Mb/s channel LI:

T (LI only, 10 Mb/s VB) $= 0.1 + 0.9258\ T_{PLI} + 18{,}936/BR_{LI}$
$+ 1.9258\ (210)$

$T_{PLI} = 1/(10/18{,}000 + 4/25{,}000 + 4/210) = 50.6$

$T = 451.3627 + 18{,}936/BR_{LI}$

50 Mb/s: $T = 0.83$
100 Mb/s: $T = 0.63$
200 Mb/s: $T = 0.53$

T (LI only, 5 Mb/s VB) = same as for 10 Mb/s VB

T (LI only, 1 Mb/s VB) = same as for 10 Mb/s VB

T (LI only, 11 Mb/s ch) $= 210 + 0.9258\ (50.6) + 18{,}936/BR_{LI}$
$+ 1.9258\ (210) = 661.26 + 18{,}936/BR_{LI}$

50 Mb/s: $T = 1.04$
100 Mb/s: $T = 0.86$
200 Mb/s: $T = 0.76$

T (LI only, Com) $= 18{,}000 + 0.9258\ (50.6) + 18{,}936/BR_{LI}$
$+ 1.9258\ (18{,}000) = 52{,}711.245 + 18{,}936/BR_{LI}$

50 Mb/s: $T = 53.09$
100 Mb/s: $T = 52.91$
200 Mb/s: $T = 52.81$

T (LI only, ADP) $= 25{,}000 + 0.9258\ (50.6) + 18{,}936/BR_{LI}$
$+ 1.9258\ (25{,}000) = 73{,}191.845 + 18{,}936/BR_{LI}$

50 Mb/s: $T = 73.57$
100 Mb/s: $T = 73.38$
200 Mb/s: $T = 73.28$

T (FI, 10 Mb/s VB) $= 0.1 + 0.9258\ (50.6) + 0.1\ (0.2)$
$+ 0.9258\ T_{PEI} + 0.9258\ T_{PLI} + 1.9258\ (210)$
$+ 75{,}744/BR_{LI} + 19{,}152/BR_{EI} + 2\ t_p$

$T_{PLI} = 1/(10/18{,}000 + 4/25{,}000 + 3/210) = 66.66$

$T_{PEI} = 1/(80/18{,}000 + 32/25{,}000 + 1/210 + 1/18{,}936 + 1/3787.2$
$+ 1/1893.6) = 88.25$

$T = 594.8 + 75{,}744/BR_{LI} + 19{,}152/BR_{EI} + 2\ t_p$

LI = 50 Mb/s; EI = 100 Mb/s: T = 2.66 (1 km)
= 2.81 (16 km)

LI = 100 Mb/s; EI = 50 Mb/s: T = 2.09 (1 km)
= 2.24 (16 km)

LI = 100 Mb/s; EI = 100 Mb/s: T = 1.90 (1 km)
= 2.05 (16 km)

LI = 100 Mb/s; EI = 200 Mb/s: T = 1.80 (1 km)
= 1.96 (16 km)

LI = 200 Mb/s; EI = 100 Mb/s: T = 1.52 (1 km)
= 1.67 (16 km)

LI = 200 Mb/s; EI = 200 Mb/s: T = 1.42 (1 km)
= 1.58 (16 km)

T (FI, 5 Mb/s VB) = same as for 10 Mb/s VB

T (FI, 1 Mb/s VB) = same as for 10 Mb/s VB

$$\begin{aligned} T\ (\text{FI, 11 Mb/s ch}) &= 210 + 0.9258\ (50.6) + 55 + 0.5\ (210) \\ &\quad + 0.9258\ (88.25) + 95 + 0.9258\ (66.66) + 55 \\ &\quad + 1.9258\ (210) + 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\ t_p \\ &= 1114.6792 + 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\ t_p \end{aligned}$$

LI = 50 Mb/s; EI = 100 Mb/s: T = 2.85 (1 km)
= 3.16 (16 km)

LI = 100 Mb/s; EI = 50 Mb/s: T = 2.28 (1 km)
= 2.59 (16 km)

LI = 100 Mb/s; EI = 100 Mb/s: T = 2.09 (1 km)
= 2.40 (16 km)

LI = 100 Mb/s; EI = 200 Mb/s: T = 1.99 (1 km)
= 2.30 (16 km)

LI = 200 Mb/s; EI = 100 Mb/s: T = 1.71 (1 km)
= 2.01 (16 km)

LI = 200 Mb/s; EI = 200 Mb/s: T = 1.61 (1 km)
= 1.92 (16 km)

$$\begin{aligned} T\ (\text{FI, Com}) &= 18{,}000 + 0.9258\ (50.6) + 55 + 9000 + 0.9258\ (88.25) \\ &\quad + 95 + 0.9258\ (66.66) + 55 + 1.9258\ (18{,}000) \\ &\quad + 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\ t_p \\ &= 62{,}059.661 + 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\ t_p \end{aligned}$$

LI = 50 Mb/s; EI = 100 Mb/s: T = 63.79 (1 km)
= 64.10 (16 km)

LI = 100 Mb/s; EI = 50 Mb/s: T = 63.22 (1 km)
= 63.53 (16 km)

LI = 100 Mb/s; EI = 100 Mb/s: T = 63.03 (1 km)
= 63.34 (16 km)

LI = 100 Mb/s; EI = 200 Mb/s: T = 62.93 (1 km)
= 63.24 (16 km)

LI = 200 Mb/s; EI = 100 Mb/s: T = 63.65 (1 km)
= 62.96 (16 km)

LI = 200 Mb/s; EI = 200 Mb/s: T = 62.55 (1 km)
= 62.86 (16 km)

$$\begin{aligned} T\ (\text{FI, ADP}) &= 25{,}000 + 0.9258\ (50.6) + 55 + 12{,}500 + 0.9258\ (88.25) \\ &+ 95 + 0.9258\ (66.66) + 55 + 1.9258\ (25{,}000) \\ &+ 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\ t_p = 86{,}040.261 \\ &+ 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\ t_p \end{aligned}$$

LI = 50 Mb/s; EI = 100 Mb/s: T = 87.77 (1 km)
= 88.08 (16 km)

LI = 100 Mb/s; EI = 50 Mb/s: T = 87.20 (1 km)
= 87.51 (16 km)

LI = 100 Mb/s; EI = 100 Mb/s: T = 87.01 (1 km)
= 87.29 (16 km)

LI = 100 Mb/s; EI = 200 Mb/s: T = 86.91 (1 km)
= 87.23 (16 km)

LI = 200 Mb/s; EI = 100 Mb/s: T = 86.63 (1 km)
= 86.94 (16 km)

LI = 200 Mb/s; EI = 200 Mb/s: T = 86.53 (1 km)
= 86.84 (16 km)

For other LIs:

T (LI only, 10 Mb/s VB) = same as for 5 Mb/s VB on 11 Mb/s ch LI in Scenario 1

T (LI only, 5 Mb/s VB) = same as for 10 Mb/s VB

T (LI only, 1 Mb/s VB) = same as for 10 Mb/s VB

T (LI only, Com) = same as for Com on 11 Mb/s ch LI in Scenario 1

T (LI only, ADP) = same as for ADP on 11 Mb/s ch LI in Scenario 1

$$\begin{aligned} T\ (\text{FI, 10 Mb/s VB}) &= 0.1 + 0.9258\ (66.66) + 0.5\ (0.1) \\ &+ 0.9258\ (88.25) + 0.9258\ (66.66) \\ &+ 1.9258\ (210) + 75{,}744/BR_{LI} + 19{,}152/BR_{EI} \\ &+ 2\ t_p = 609.69751 + 75{,}744/BR_{LI} \\ &+ 19{,}152/BR_{EI} + 2\ t_p \end{aligned}$$

LI = 50 Mb/s; EI = 100 Mb/s: T = 2.67 (1 km)
= 2.82 (16 km)

LI = 100 Mb/s; EI = 50 Mb/s: T = 2.10 (1 km)
= 2.25 (16 km)

LI = 100 Mb/s; EI = 100 Mb/s: T = 1.91 (1 km)
= 2.06 (16 km)

LI = 100 Mb/s; EI = 200 Mb/s: T = 1.81 (1 km)
= 1.97 (16 km)

LI = 200 Mb/s; EI = 100 Mb/s: T = 1.53 (1 km)
= 1.68 (16 km)

LI = 200 Mb/s; EI = 200 Mb/s: T = 1.43 (1 km)
= 1.59 (16 km)

T (FI, 5 Mb/s VB) = T (FI, 1 Mb/s VB) = T (FI, 10 Mb/s VB)

$$\begin{aligned} T\ (\mathrm{FI,\ Com}) &= 18{,}000 + 0.9258\ (66.66) + 55 + 9000 + 0.9258\ (88.25) \\ &\quad + 95 + 0.9258\ (66.66) + 55 + 1.9258\ (18{,}000) \\ &\quad + 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\ t_p \\ &= 62{,}074.53 + 76{,}104/BR_{LI} + 19{,}188/BR_{EI} + 4\ t_p \end{aligned}$$

LI = 50 Mb/s; EI = 100 Mb/s: T = 63.80 (1 km)
= 64.11 (16 km)

LI = 100 Mb/s; EI = 50 Mb/s: T = 63.21 (1 km)
= 63.54 (16 km)

LI = 100 Mb/s; EI = 100 Mb/s: T = 63.04 (1 km)
= 63.35 (16 km)

LI = 100 Mb/s; EI = 200 Mb/s: T = 62.94 (1 km)
= 63.25 (16 km)

LI = 200 Mb/s; EI = 100 Mb/s: T = 63.65 (1 km)
= 62.97 (16 km)

LI = 200 Mb/s; EI = 200 Mb/s: T = 62.56 (1 km)
= 62.87 (16 km)

$$\begin{aligned} T\ (\mathrm{FI,\ ADP}) &= 25{,}000 + 0.9258\ (66.66) + 55 + 12{,}500 + 0.9258\ (88.25) \\ &\quad + 95 + 0.9258\ (66.66) + 55 + 1.9258\ (25{,}000) + 76{,}104/BR_{LI} \\ &\quad + 19{,}188/BR_{EI} + 4\ t_p = 86{,}055.13 + 76{,}104/BR_{LI} \\ &\quad + 19{,}188/BR_{EI} + 4\ t_p \end{aligned}$$

LI = 50 Mb/s; EI = 100 Mb/s: T = 87.78 (1 km)
= 88.09 (16 km)

LI = 100 Mb/s; EI = 50 Mb/s: T = 87.21 (1 km)
= 87.52 (16 km)

LI = 100 Mb/s; EI = 100 Mb/s:	T = 87.02 (1 km)	
	= 87.30 (16 km)	
LI = 100 Mb/s; EI = 200 Mb/s:	T = 86.92 (1 km)	
	= 87.24 (16 km)	
LI = 200 Mb/s; EI = 100 Mb/s:	T = 86.64 (1 km)	
	= 86.95 (16 km)	
LI = 200 Mb/s; EI = 200 Mb/s:	T = 86.54 (1 km)	
	= 86.85 (16 km)	

Calculations: Bus Rates

PR = Packet Rate
BR = Bit Rate
τ = Propagation Delay
DA = Direct Address
VB = Virtual Bus

Scenario a

PR (LI) = 1 LIU/18 ms = 55.556 p/s (VB)

BR (LI) = 55.556 (19,080 b/p) = 1.06 Mb/s

Scenario b

PR (LI) = 5 LIUs/18 ms = 277.78 p/s (VB)

BR (LI) = 277.78 (19,080 b/p) = 5.3 Mb/s

Scenario c

PR (LI) = 55.556 p/s (VB) + 2 (55.556 p/s) (DA)
= 55.556 p/s (VB) + 111.111 p/s (DA)

BR (LI) = 19,080 (55.556) + 2 (19,260) (55.556/(1 - 55.556 x 55 μs))
= 1.060 + 2.147 = 3.207 Mb/s

PR (EI) = (3 LIs) (55.556) = 166.667 p/s (DA)

BR (EI) = (3 LIs) (19,368) (55.556/(1 - (55.556) (95 μs + τ)))

τ = 4 (5.1) = 20.4 μs for 1 km
= 4 (81.6) = 326.4 μs for 16 km

BR (EI) = 3.25 Mb/s for 1 km
= 3.31 Mb/s for 16 km

Scenario d

PR (LI) = 277.78 p/s (VB) + 2 (277.78 p/s) (DA)
= 277.78 p/s (VB) + 555.56 p/s (DA)

BR (LI) = 277.78 (19,080) + 2 (19,260) (277.78/(1 - 277.78 x 55 μs))
= 5.3 + 10.866 = 16.166 Mb/s

PR (EI) = (3 LIs) (277.78) = 833.34 p/s (DA)

BR (EI) = (3 LIs) (19,368) (277.78/(1 - (277.78) (95 μs + τ)))
= 16.675 Mb/s for 1 km
= 18.280 Mb/s for 16 km

Scenario e

PR (LI) = (10 LIUs/18 ms) (VB) + 2 (10 LIUs/18 ms) (DA)
= 555.556 p/s (VB) + 1111.111 p/s (DA)

BR (LI) = 555.556 (19,080) + 2 (19,260) (555.556/(1 - 555.556 x 55 μs)
= 10.6 + 22.07 = 32.67 Mb/s

PR (EI) = (8 LIs) (555.556) = 4444.44 p/s (DA)

BR (EI) = (8 LIs) (19,368) (555.556/(1 - (555.556) (95 μs + τ)))
= 91.977 Mb/s for 1 km
= 112.39 Mb/s for 16 km

Scenario f

PR (LI) = 555.556 p/s (VB) + 2 (555.556 p/s
+ 4 LIUs/25 ms) (DA)
= 555.556 p/s (VB) + 1431.112 p/s (DA)

BR (LI) = 32.67M + 2 (19,260) (160/(1 - 160 x 55 μs)
= 32.67 + 6.218 = 38.89 Mb/s

PR (EI) = (8 LIs) (555.556 + 160) = 5724.44 p/s (DA)

BR (EI) = BR (EI)_e + (8 LIs) (19,368) (160/(1 - (160) (95 μs + τ)))
= 91.977 + 25.257 = 117.23 Mb/s for 1 km
= 112.39 + 26.583 = 138.97 Mb/s for 16 km

Scenario g

PR (LI) = 555.556 p/s (VB) + 1431.112 p/s (DA)
+ (11 Mb/s) (1 w/78 b)/(1024 w) (DA)
= 555.556 p/s (VB) + 2027.9 p/s (DA)

BR (LI) = 38.89M + 2 (19,260) (596.79/(1 - 596.79 x 55 μs)
= 38.89 + 23.768 = 62.66 Mb/s

PR (EI) = 5724.44 + 596.79 = 6321.23 p/s (DA)

BR (EI) = BR (EI)_f + (8 LIs) (19,368) (596.79/(1 - (596.79) (95 μs + τ)))
= 117.23 + 99.31 = 216.54 Mb/s for 1 km
= 138.97 + 123.54 = 262.51 Mb/s for 16 km

Scenario h

PR (LI) = 555.556 p/s (VB) + 2027.9 p/s (DA)
+ (1 Mb/s) (1 w/18 b)/(1024 w) (VB)
= 609.81 p/s (VB) + 2027.9 p/s (DA)

BR (LI) = 62.66M + 54.25 (19,080) = 62.66 + 1.035
= 63.695 Mb/s

PR (EI) = 6321.23 p/s (DA) + 54.25 p/s (VB)

$$BR\ (EI) = BR\ (EI)_g + (19{,}152)\ (54.25/(1 - 54.25\ \tau))$$

$$\tau = 2\ (5.1) = 10.2\ \mu s \text{ for } 1 \text{ km}$$
$$= 2\ (81.6) = 163.2\ \mu s \text{ for } 16 \text{ km}$$

$$BR\ (EI) = 216.54 + 1.04 = 217.58 \text{ Mb/s for } 1 \text{ km}$$
$$= 262.51 + 1.05 = 263.56 \text{ Mb/s for } 16 \text{ km}$$

Scenario i

$$PR\ (LI) = 609.81 \text{ p/s (VB)} + 2027.9 \text{ p/s (DA)}$$
$$+ (5 \text{ Mb/s})\ (1 \text{ w}/18 \text{ b})/(1024 \text{ w})\ \text{(VB)}$$
$$= 881.08 \text{ p/s (VB)} + 2027.9 \text{ p/s (DA)}$$

$$BR\ (LI) = 63.695M + 271.27\ (19{,}080) = 63.695 + 5.176$$
$$= 68.87 \text{ Mb/s}$$

$$PR\ (EI) = 6321.23 \text{ p/s (DA)} + 325.52 \text{ p/s (VB)}$$

$$BR\ (EI) = BR\ (EI)_h + (19{,}152)\ (271.27/(1 - 271.27\ \tau))$$
$$= 217.58 + 5.21 = 222.79 \text{ Mb/s for } 1 \text{ km}$$
$$= 263.56 + 5.44 = 269.00 \text{ Mb/s for } 16 \text{ km}$$

Scenario j

$$PR\ (LI) = 881.08 \text{ p/s (VB)} + 2027.9 \text{ p/s (DA)}$$
$$+ (10 \text{ Mb/s})\ (1 \text{ w}/18 \text{ b})/(1024 \text{ w})\ \text{(VB)}$$
$$= 1423.61 \text{ p/s (VB)} + 2027.9 \text{ p/s (DA)}$$

$$BR\ (LI) = 68.87\ M + 542.53\ (19{,}080) = 68.87 + 10.35$$
$$= 79.22 \text{ Mb/s}$$

$$PR\ (EI) = 6321.23 \text{ p/s (DA)} + 868.05 \text{ p/s (DA)}$$

$$BR\ (EI) = BR\ (EI)_i + (19{,}152)\ (542.53/(1 - 542.53\ \tau))$$
$$= 222.79 + 10.45 = 233.24 \text{ Mb/s for } 1 \text{ km}$$
$$= 269.00 + 11.40 = 280.40 \text{ Mb/s for } 16 \text{ km}$$

Calculations: Blockage of a Designated Message

Scenario a
1.06 Mb/s < 50 Mb/s
No blockage

Scenario b
5.3 Mb/s < 50 Mb/s
No blockage

Scenario c
3.207 Mb/s < 50 Mb/s
No blockage on LI

3.25 & 3.31 Mb/s < 50 Mb/s
No blockage on EI

Scenario d
16.166 Mb/s < 50 Mb/s
No blockage on LI

16.675 & 18.280 Mb/s < 50 Mb/s
No blockage on EI

Scenario e
32.67 Mb/s < 50 Mb/s
No blockage on LI

200 Mb/s (EI):
    91.977 & 112.39 Mb/s < 200 Mb/s
    No blockage

100 Mb/s (EI):
    91.977 Mb/s < 100 Mb/s
    No blockage for 1 km

    $P_{LIU} = 1 - 100/112.39 = 0.110$ for 16 km

50 Mb/s (EI):
    $P_{LIU} = 1 - 50/91.977 = 0.456$ for 1 km

    $P_{LIU} = 1 - 50/112.39 = 0.555$ for 16 km

Scenario f
38.89 Mb/s < 50 Mb/s
No blockage on LI

200 Mb/s (EI):
    117.23 & 138.97 Mb/s < 200 Mb/s
    No blockage

100 Mb/s (EI):

$P_{LIU} = 1 - 100/117.23 = 0.147$ for 1 km

$P_{LIU} = 1 - 100/138.97 = 0.280$ for 16 km

50 Mb/s (EI):

$P_{LIU} = 1 - 50/117.23 = 0.573$ for 1 km

$P_{LIU} = 1 - 50/138.97 = 0.640$ for 16 km

Scenario g

200 Mb/s (LI):

62.66 Mb/s < 200 Mb/s

No blockage

100 Mb/s (LI):

62.66 Mb/s < 100 Mb/s

No blockage

50 Mb/s (LI):

$P_{LIU} = 1 - 50/62.66 = 0.202$

200 Mb/s (EI):

$P_{LIU} = 1 - 200/216.54 = 0.076$ for 1 km

$P_{LIU} = 1 - 200/262.51 = 0.238$ for 16 km

100 Mb/s (EI):

$P_{LIU} = 1 - 100/216.54 = 0.538$ for 1 km

$P_{LIU} = 1 - 100/262.51 - 0.619$ for 16 km

50 Mb/s (EI):

$P_{LIU} = 1 - 50/216.54 = 0.769$ for 1 km

$P_{LIU} = 1 - 50/262.51 = 0.810$ for 16 km

Scenario h

200 Mb/s (LI):

63.695 Mb/s < 200 Mb/s

No blockage

100 Mb/s (LI):

63.695 Mb/s < 100 Mb/s

No blockage

50 Mb/s (LI):

$P_{LIU} = 1 - 50/63.695 = 0.215$

200 Mb/s (EI):

$P_{LIU} = 1 - 200/217.58 = 0.808$ for 1 km

$P_{LIU} = 1 - 200/263.56 = 0.241$ for 16 km

100 Mb/s (EI):

$P_{LIU} = 1 - 100/217.58 = 0.540$ for 1 km

$P_{LIU} = 1 - 100/263.56 = 0.621$ for 16 km

50 Mb/s (EI):

$P_{LIU} = 1 - 50/217.58 = 0.770$ for 1 km

$P_{LIU} = 1 - 100/263.56 = 0.810$ for 16 km

<u>Scenario i</u>

200 Mb/s (LI):

68.87 Mb/s < 200 Mb/s

No blockage

100 Mb/s (LI):

68.87 Mb/s < 100 Mb/s

No blockage

50 Mb/s (LI):

$P_{LIU} = 1 - 50/68.87 = 0.274$

200 Mb/s (EI):

$P_{LIU} = 1 - 200/222.79 = 0.102$ for 1 km

$P_{LIU} = 1 - 200/269 = 0.257$ for 16 km

100 Mb/s (EI):

$P_{LIU} = 1 - 100/222.79 = 0.551$ for 1 km

$P_{LIU} = 1 - 100/269 = 0.628$ for 16 km

50 Mb/s (EI):

$P_{LIU} = 1 - 50/222.79 = 0.776$ for 1 km

$P_{LIU} = 1 - 50/269 = 0.814$ for 1 km

<u>Scenario j</u>

200 Mb/s (LI):

79.22 Mb/s < 200 Mb/s

No blockage

100 Mb/s (LI):

79.22 Mb/s < 100 Mb/s

No blockage

50 Mb/s (LI):

$P_{LIU} = 1 - 50/79.22 = 0.631$

200 Mb/s (EI):

$P_{LIU} = 1 - 200/233.24 = 0.143$ for 1 km

$P_{LIU} = 1 - 200/280.40 = 0.287$ for 16 km

100 Mb/s (EI):

$P_{LIU} = 1 - 100/233.24 = 0.571$ for 1 km

$P_{LIU} = 1 - 100/280.40 = 0.643$ for 16 km

50 Mb/s (EI):

$P_{LIU} = 1 - 50/233.24 = -.786$ for 1 km

$P_{LIU} = 1 - 50/280.40 = 0.822$ for 16 km

Calculations: Blockage on the FI

(5.4.2.1) Scenario e

Mean = $\bar{X}$ = 8.9 LIUs/LI

$$\text{Variance} = d^2 = 1/n \sum_{i=1}^{n} (Xi - \bar{X})^2 = 0.64$$

Standard deviation = d = 0.8

200 Mb/s: No blockage

100 Mb/s: No blockage for 1 km

X = (10 LIUs/LI) (100/112.39) = 8.898
Z = (8.9 - 8.898)/0.8 = 0.003
P_{FI} = 0.5012 for 16 km

50 Mb/s:

X = (10) (50/91.977) = 5.436
Z = (8.9 - 5.436)/0.8 = 4.33
P_{FI} = 1 for 1 km

X = (10) (50/112.39) = 4.449
Z = (8.9 - 4.449)/0.8 = 5.564
P_{FI} = 1 for 16 km

(5.4.2.2) Scenario f

$\bar{X}$ (Com) = 8.9 $\bar{X}$ (ADP) = 3.5
$\bar{X}$ (Total) = 8.9 + 3.5 = 12.4

d^2 (Com) = 0.75 d^2 (ADP) = 0.735
d^2 (Total) = 0.75 + 0.735 = 1.485

$d = \sqrt{1.485} = 1.219$

200 Mb/s: No blockage

100 Mb/s:

X = (10) (100/117.23) = 8.53
Z = (12.4 - 8.53)/1.219 = 3.175
P_{FI} = 0.99904 for 1 km

X = (10) (100/138.97) = 7.196
Z = (12.4 - 7.196)/1.219 = 4.269
P_{FI} = 1 for 16 km

50 Mb/s: P_{FI} = 1

(5.4.2.3) <u>Scenario g</u>

For 11 Mb/s channel LI -- $\bar{X} = 12.4 + 1 = 13.4$

200 Mb/s:

$X = (10)\ (200/216.54) = 9.236$
$Z = (13.4 - 9.236)/1.219 = 3.416$
$P_{FI} = 0.99970$ for 1 km

$X = (10)\ (200/262.51) = 7.619$
$Z = (13.4 - 7.619)/1.219 = 4.743$
$P_{FI} = 1$ for 16 km

100 Mb/s:

$X = 10\ (100/216.54) = 4.618$
$Z = (13.4 - 4.618)/1.219 = 7.2$
$P_{FI} = 1$ for 1 km

$P_{FI} = 1$ for 16 km

50 Mb/s: $P_{FI} = 1$

For other LIs -- $\bar{X} = 12.4$

200 Mb/s:

$X = 9.236$
$Z = (12.4 - 9.236)/1.219 = 2.596$
$P_{FI} = 0.9953$ for 1 km

$X = 7.619$
$Z = (12.4 - 7.619)/1.219 = 3.922$
$P_{FI} = 0.99996$ for 16 km

100 Mb/s:

$X = 4.618$
$Z = (12.4 - 4.618)/1.219 = 6.38$
$P_{FI} = 1$ for 1 km

$P_{FI} = 1$ for 16 km

50 Mb/s:

$P_{FI} = 1$

(5.4.2.4) Scenario h

For 11 Mb/s channel LI -- $\bar{X}$ = 13.4

200 Mb/s:

$X = (10)\ (200/217.58) = 9.192$

$Z = (13.4 - 9.192)/1.219 = 3.452$

$P_{FI} = 0.99976$ for 1 km

$P_{FI} = 1$ for 16 km

100 Mb/s: $P_{FI} = 1$

50 Mb/s: $P_{FI} = 1$

For other LIs -- $\bar{X}$ = 12.4

200 Mb/s:

$X = 9.192$

$Z = (12.4 - 9.192)/1.219 = 2.632$

$P_{FI} = 0.9965$ for 1 km

$X = (10)\ (200/263.56) = 7.588$

$Z = (12.4 - 7.588)/1.219 = 3.947$

$P_{FI} = 0.99990$ for 16 km

100 Mb/s: $P_{FI} = 1$

50 Mb/s: $P_{FI} = 1$

(5.4.2.4) Scenario i

For 11 Mb/s channel LI -- $\bar{X}$ = 13.4

200 Mb/s:

$X = (10)\ (200/222.79) = 8.977$

$Z = (13.4 - 8.977)/1.219 = 3.628$

$P_{FI} = 0.99991$ for 1 km

$P_{FI} = 1$ for 16 km

100 Mb/s: $P_{FI} = 1$

50 Mb/s: $P_{FI} = 1$

For other LIs -- $\bar{X} = 12.4$

200 Mb/s:

$X = 8.977$
$Z = (12.4 - 8.977)/1.219 = 2.808$
$P_{FI} = 0.99779$ for 1 km

$X = (10)\ (200/269) = 7.435$
$Z = (12.4 - 7.435)/1.219 = 4.073$
$P_{FI} = 0.999976$ for 16 km

100 Mb/s: $P_{FI} = 1$

50 Mb/s: $P_{FI} = 1$

(5.4.2.4) <u>Scenario j</u>

For 11 Mb/s channel LI -- $\bar{X} = 13.4$

200 Mb/s:

$X = (10)\ (200/233.24) = 8.575$
$Z = (13.4 - 8.575)/1.219 = 3.958$
$P_{FI} = 0.999968$

$P_{FI} = 1$ for 16 km

100 Mb/s: $P_{FI} = 1$

50 Mb/s: $P_{FI} = 1$

For other LIs -- $\bar{X} = 12.4$

200 Mb/s:

$X = 8.575$
$Z = (12.4 - 8.575)/1.219 = 3.138$
$P_{FI} = 0.9991$ for 1 km

$X = (10)\ (200/280.4) = 7.133$
$Z = (12.4 - 7.133)/1.219 = 4.32$
$P_{FI} = 1$ for 16 km

100 Mb/s: $P_{FI} = 1$

50 Mb/s: $P_{FI} = 1$

6.0 CONCLUSIONS

a. Queuing delays occur at the rate interface on the FI and are due to asynchronous polling, messages non-uniformally spaced in the polling cycle, and non-isochronous polling intervals. These polling irregularities are assumed to be Gaussian distributed. A queuing delay of .9258 P_n results where P_n is the average polling interval on the intraconnect which is receiving the message.

b. The fact that 100% off-hook factors were used in this analysis for both Com and ADP restricts the usefulness of the results. A follow-on analysis should be made which takes into account a random placement of telephone calls and ADP users and uses realistic call holding times. Meaningful blockage probabilities and information throughput results can be derived in this way.

c. A wide range of packet throughput times has been calculated showing the effects of polling intervals, query/response times, queuing delays, and propagation delays over the fiber optic cable. These times ranged from 0.83 ms for a 1 Mb/s virtual bus on a 200 Mb/s LI and 200 Mb/s, 1 km EI to 102.79 ms for a Com packet to traverse a 50 Mb/s LI and 100 Mb/s, 16 km EI (Scenario c).

d. From the calculation of the transmission rates required for each scenario it can be seen that the length of the EI has a major effect on the effective bandwidth required. For instance, Scenario j shows that a 16 km EI requires 47.16 Mb/s more bandwidth to transmit the same information as a 1 km EI.

7.0 RECOMMENDATIONS FOR FURTHER STUDY

7.1 Recommendations for a Comprehensive Throughput Analysis.

This traffic analysis is based on two assumptions which were imposed as simplifications. They are, 1) a 100% duty (off-hook) factor for all devices, and 2) all messages contain 1,024 data words. While serving to simplify the analyses, these assumptions are unrealistic, and pose serious limitations in determining true blocking probabilities and traffic capacities of the FI. Not only do these assumptions result in implications that the system blocks at relatively light loads, but they do not exercise the query-response function or the buildup of a message queue from traffic loading. This is because when it is known that all devices are off-hook 100% of the time the system can be loaded only to the point thet the LI or EI capacity is reached, and all other devices are blocked <u>prior</u> to entering the system. Those denied access comprise a "percentage" of blocking. This is not a probability of blocking because the quantities of both users and those denied access is fixed, or certain, once the scenario is established. When fixed in this manner, the capacity of the system is never exceeded at any point because once a message is on the FI, there is always capacity to send it to its destination without the possibility of buffer overflow. It is only when the instantaneous offered load is greater than the instantaneous capacity that a true probability of blockage occurs. The query-response mode and buffer queue are, therefore, not exercised, or necessary under these conditions. Additionally, when the load is known and in a steady state, such as these scenarios are, it can be assumed that polling is evenly distributed in time and queue build-up due to polling irregularities is not possible. To make the preceeding analysis more meaningful it was assumed that these two conditions existed when, in fact, with the conditions imposed, they did not.

A realistic determination of system throughput capacity, and blocking probability is essential to the proper system application of the FI. Otherwise, it will be impossible to properly determine the subscriber loads which can be handled by the FI in a real deployment of TAF centers. It is for this reason that a follow-up analysis is recommended. The methodology for this analysis follows.

In a real situation where the FI will be applied, the subscribers will be off-hook only a small fraction of the time it is connected to the FI. This applies to both ADP and telephone users. It is, therefore, wasteful to provide bandwidth on the FI for 100% off-hook. If it can be determined what is a good use factor for the subscribers as a whole, the FI can be sized for that load, or conversely, given a group of subscribers with certain use characteristics and an FI with certain bandwidth capabilities, it can be determined what probability of blockage is encountered by each subscriber.

The FI presents to subscribers a certain number of transmission channels. The quantity of channels is based on the bandwidth of the LI and EI. When the number of subscribers accessing the FI exceeds the number of transmission channels, blockage occurs. There are other contributions to blockage than simple excess traffic. When the transmission of messages in bunched or irregularly spaced in time queue, build-ups tend to result and blockage occurs sooner than would otherwise be expected. Some of these factors were taken into account in this analysis, but the primary factor, that due to randomly offered loads by subscribers, was not. The analysis will address the effects of both types of blockage.

The community of subscribers offers a load to the FI which is random in both time and length of use. If the probability distribution for the sources can be determined, the blocking probability, queue delays, and maximum queue sizes can be calculated. The problem is similar to that of telephone subscribers accessing a switch. In fact, it will be useful to start the analysis by assuming that both telephone and ADP subscribers follow an Erlang probability distribution. In that way advantage can be taken of methods and tables derived earlier by telephone systems. This appears to be a valid assumption at this time.

There are two types of blocking situations; One where there is no queue buildup such as in subscribers accessing the FI at the device level, and another where a queue delay is involved. This occurs at the rate interface of the FI, i.e., device - LI, LI-EI, EI-LI, and LI-device. In the first instance an Erlang B distribution is applicable, and in the second, Erlang C applies. The variables in the Erlang B distribution of average call intensity and number of channels, and the variable call holding time used in Erlang C can be directly related to FI parameters.

The problem of traffic accessing the FI can be approached by considering the offered load to each LI individually, assuming that the LIs are not all identical. The probability of blockage can be determined by the Erlang B formula (Item 3):

$$E(c,a) = \frac{\frac{a^c}{c!}}{1 + a = \frac{a^2}{2!} + \ . \ . \ . \ \frac{a^c}{c!}}$$

where, a is mean of the offered traffic in erlangs and c is the number of service channels. Erlang B is applicable because: 1) the traffic originates from a large number of sources, 2) the number of service channels is limited, 3) the lost calls are cleared from the system with zero holding time, and 4) the distribution is valid for any distribution of call holding time, specifically either constant or negative exponential. The mean of offered traffic, a, will need to be determined so that it applies to ADP transmission as well as voice. This should be easily done since ADP "calls" should have intensity characteristics similar to voice traffic. The number of service channels, c, is determined from LI and EI bandwidths. If required, E(c,a) can be calculated, but this should not be necessary because of the availability of tables which include all conditions of interest to the FI.

The problems of blocking and queuing on the FI can be approached by application of the Erlang C formula which assumes that "lost" calls are held in queue to be serviced by the system instead of being rejected as they were in the Erlang B situation. The Erlang C formula is (Item 3):

$$E_2(c_1a) = \frac{\frac{a^c}{c!}\,\frac{c}{c-a}}{1 + a = \frac{a^2}{2!} + \frac{a^c}{c!}\,\frac{c}{c-a}}$$

This formula can be applied to LI-to-EI access, EI-to-LI access and LI-to-device access by properly interpreting the call intensity, a, in terms of LIU loads offered to the LI, EIU loads offered to the EI, and LI loads offered to the device. $E_2(c,a)$ is interpreted as the probability of delay. The following queue determination can be made from this formula (Item 3):

1) Probability of delay when the que length is limited to q places;

$$P(>0) = \frac{\frac{a}{c!}\,\frac{c}{c-a}\left(1 - \frac{a}{c}\right)^{8+1}}{1 + a + \frac{a^2}{2} + \ldots\ldots\ldots\ldots \frac{a^c}{c!}\,\frac{c}{c-a}\left(1 - \frac{a}{c}\right)^{q+1}}$$

2) Probability of delay in excess of t, or P (>t).

$$P(>t) = P(>0)\ e^{-(c-a)t/h}$$

where h is the average call holding time.

3) Probability of loss;

$$L = \frac{a^q}{\frac{1}{B} + a\,\frac{(1-a^8)}{1-a}}$$

where B is given by the Erlang B formula,

4) Average delay on all calls;

$$\bar{d} = P(>0) \cdot \frac{h}{c-a}$$

5) Average delay on delayed calls;

$$\bar{d} = \frac{h}{c-a}$$

6) Length of que,

$Q(\geq q)$ and $\bar{q}$;

a) The probability of que length equal to or exceeding

$$q: \quad Q(\geq q) = \left(\frac{a}{c}\right)^{8} P(>0)$$

b) Average length of que: $\bar{q} = P(>0)\ \frac{a}{c-a}$.

It will be useful to adapt the model which was made in this analysis to the foregoing traffic considerations. The model can then be simulated on a computer or hand calculated if the number of scenarios is small. A computer simulation would allow a wide range of scenarios to be exercised. It would be possible to produce graphs of blocking and queue parameters as a function of LI and EI bandwidths and subscriber loads.

This type of analysis is essential to understanding the traffic throughput capabilities of the FI, and to applying FI to TAF centers. Therefore, it is recommended that this analysis be performed as a follow-on to the preliminary work done so far.

7.2 Maximum Queue Determination from Nonisochronous Polling.

Maximum queue sizing was not a consideration in this analysis. In the recommendations for further study (7-1) it was recommended that an analysis of blocking and throughput be made that included queue size determination. Queue size in that context was due only to traffic loads, not to irregularities in polling intervals. It is necessary to consider all sources of queue buildup to determine maximum queue sizes and delays. The source of queue buildup addressed here is due to the effect of a "bunched" load offered to the EI from the LI, the LI from the EI, or the LIU from the LI. This effect was explained in section 5.2 but was not calculated. This determination should be made in a follow-on analysis and combined with the results of section 6.1.

Traffic may be offered from an LI to an EI, or vice-versa, at random time intervals with reference to the polling cycle of the receiving intraconnect. A queue delay based on a Gaussian distribution of polling intervals was determined. This however, did not result in a maximum queue size. One way to determine the maximum queue size is to assume an acceptable limit on the probability of queue delay and calculate the size of queue which will not exceed that limit. But the distribution of polling intervals is not certain to be Gaussian. An alternate way has been determined. Both ways can be evaluated for best results.

The size of the queue is a function of the difference of message rates on the LI and EI. While the average rate of message generation on the LI of messages destined for the EI must be equal to the polling rate to that LI the LI may generate messages instantaneously at a faster rate than the FI can accept them. These messages must go into queue. The maximum size of the queue is determined when all messages destined for the EI during one EI polling cycle are offered to the EI (LICU) buffer during the first part of the polling cycle. This condition is depicted in Figure 7-1.

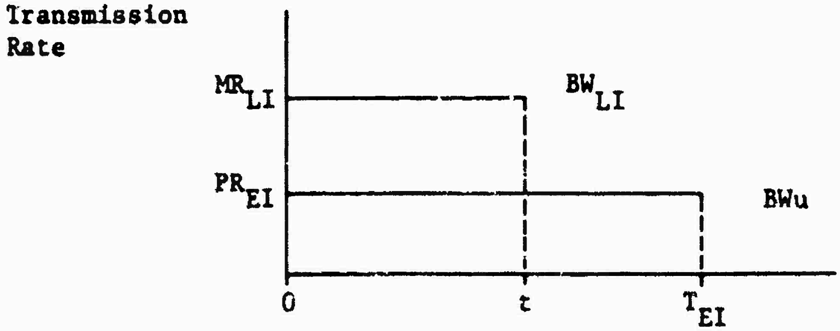

Figure 7-1. LI/EI message rate.

During the time from 0 to T_{EI}, the polling interval of the EI, the LI is generating messages into the EI (LICU) buffer at its maximum rate, i.e., proportional to the bandwidth of the LI, BW_{LI}, and the EI is depleting the buffer at a rate proportional to the polling rate of the EI. The polling rate of the EI for that LICU is proportional to the bandwidth of the LI users destined for the EI, BWu. During time, t, all messages will be generated and by time T_{EI} all will be transferred to the EI through the queuing buffer. Maximum queue will occur at time t, as shown in Figure 7-2. The queue will buildup at the difference between the LI bandwidth, BW_{LI}, and the bandwidth of LI to EI users on that LI, BW_u until time t when messages will be depleted from the buffer at the rate BWu. The maximum queue point which denotes the maximum queue buffer required, M_q can be determined from.

$$M_q = (MR_{LI} - PR_{EI})t \text{ messages.}$$

$$M_q = \frac{BW_{LI}}{18,936}$$ messages/s where each message contains 18,936 bits.

$$PR_{EI} = \frac{BW_u}{18,936} \text{ m/s}$$

$$M_q = \frac{BW_{LI} - BW_u}{18,936} \times t \text{ messages}$$

$$BW_{LI} \; t = BW_u \; T_{EI}$$

$$t = \frac{BW_u}{BWu} \; T_{EI}$$

$$M_q = \frac{BW_u - BW_u}{18,936} \; \frac{BW_u}{BW_{LI}} \; T_{EI} \text{ messages}$$

This is expression for transfer from the LI to the EI. The transfer from EI to LI is the same except EI and LI subscripts are interchanged. The transfer from LI to LIU (device) is made by:

$$M_q = \frac{BW_{LI} - BW_u}{18,936} \; \frac{BW_u}{BW_u} \; T_{LI}$$

where T_{LI} is the poll period of the LI and BW_u is the bandwidth of all users offering traffic to the device from both EI and LI sources.

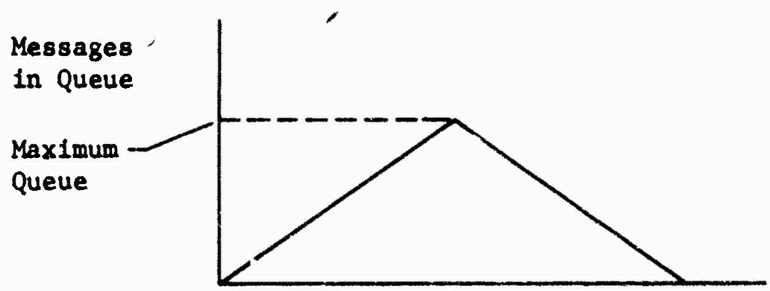

Figure 7-2. LI/EI queue occupancy.

7.3 Revised Communication SAU Design Requirements

It was determined in Task I of the study that communication SAUs should service ten telephones, provide the functions required for electrically interfacing with an LIU such as digitizing and conversion to the standard interface, and device message formatting. It has become apparent in this analysis that certain changes could be made to the SAU to greatly increase its efficiency and reduce bandwidth requirements for the FI.

By formatting the telephones in groups of ten, the LIU is forced to formulate and transmit more than one message when the phones are not all routed to the same destination. Conceivably, the LIU might be required to formulate and transmit ten point-to-point messages if each phone were destined for a different LIU. In practice, there will be fewer than ten destinations, usually only two, the switch and tech control; but up to ten may be possible when transmitting from the switch or tech control to multiple users. In addition, telephones may be assigned to SAUs according to their destination to considerably reduce the diversity of destinations from one LIU. Nevertheless, there will still be considerable inefficiency in formulating point-to-point messages in the LIU.

It is recommended that instead of providing an SAU for each LIU that one SAU be provided per shelter. This LIU would have a separate output over the standard interface to each LIU in the shelter. Refer to Figure 7-3. All telephones in the shelter would be connected to this SAU. The SAU could then be programmed by the FI manager to group telephones to LIUs by destination. This would insure the transmission of only one message per 18 ms poll interval from each LIU, instead of up to ten per poll interval. In addition to conserving bandwidth on the FI, this would allow for bulk digitizing of all telephones in one unit.

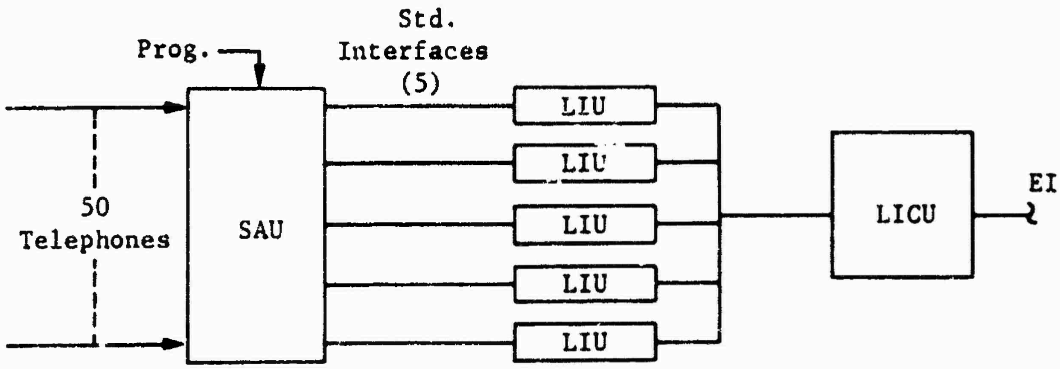

Figure 7-3. Revised SAU design.

Another consideration that would conserve bandwidth on the LI is the inclusion of intercom call processing in the SAU. This has been considered before for other reasons, i.e., call processing of all telephones on the FI for the purpose of eliminating certain circuit switch traffic. If intercom call processing were to be done in the SAU it would eliminate the need for using the virtual bus mode for intercom. Intercom calls would then be treated as point-to-point within an LI. Then all LIUs would not need to process all intercom messages only the ones addressed to it. This would simplify telephone LIU protocol somewhat by eliminating the need to deal with two types of messages.

It is recommended: 1) That the SAU functional requirements be revised to include the connection of up to 50 telephones with outputs to five LIUs over standard interfaces and have the inputs programmable to any output in groups of up to ten telephones, and 2) intercom call processing be included at the SAU level.

7.4 COMSEC Considerations.

A realistic throughput analysis cannot be completed without consideration for the impact made by COMSEC equipment. The EIU-to-LICU transfer of data is dependent upon decrypting each header in the EI to determine the address destination. Time delays encountered in the COMSEC equipment at this point can be substantial and depend greatly upon the system scheme and COMSEC device used. These delays, that were not included in this study, should be determined subsequently.

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